RF GaN Modeling for 5G and Other Applications

Mark Dunn, Raj Sodhi

EEsof DES Marketing

KEYSIGHT TECHNOLOGIES

Webinar Outline

GaN RF Devices – Market Trends, Technology, Applications, Challenges

GaN model survey

Core model descriptions:
Angelov-GaN, MVSG, ASM-HEMT and DynaFET models

Model parameter extraction

Using large signal measurements for more accurate parameter determination.

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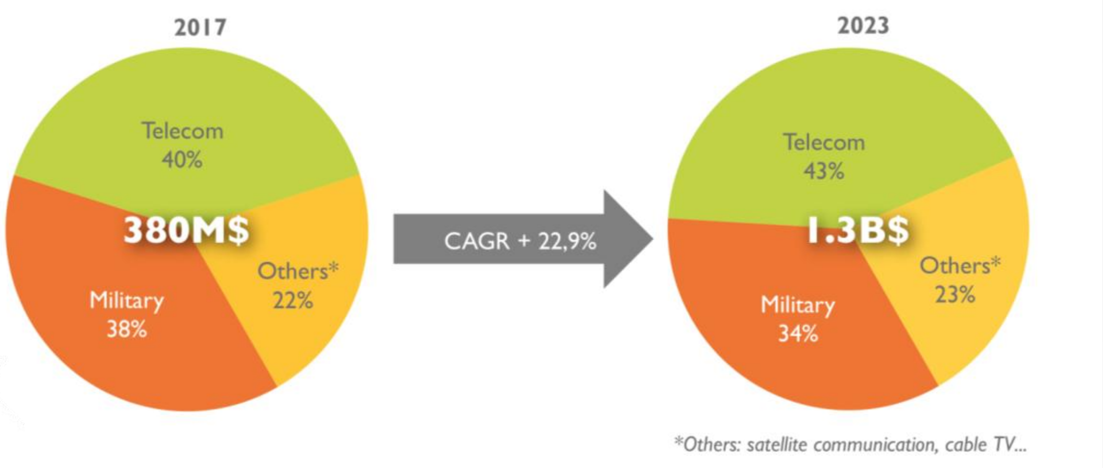
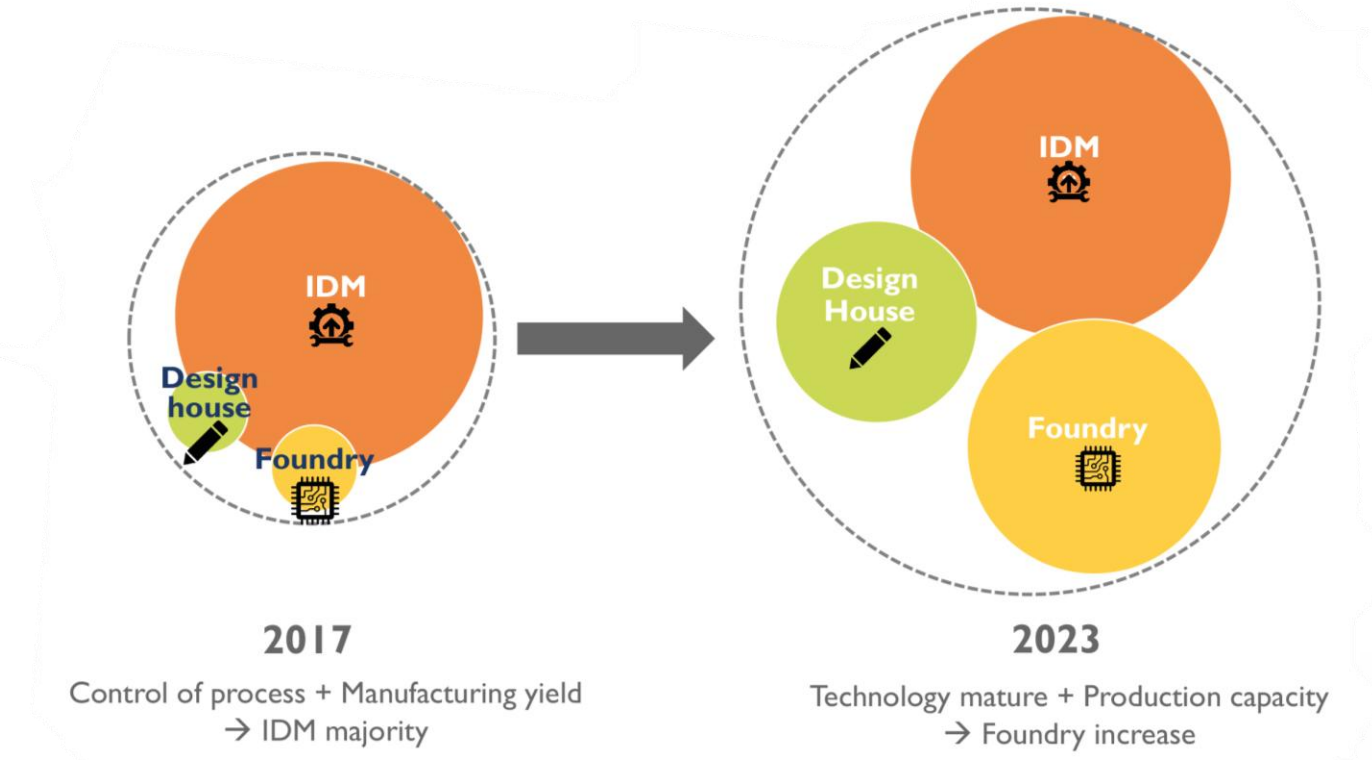
GaN Power RF - 5Y Overview

- RF GaN market to grow from $380M to $1.3B, 23% CAGR
- Market share: from 20% today to 50% by 2023
- From IDM to Fabless/Foundry model





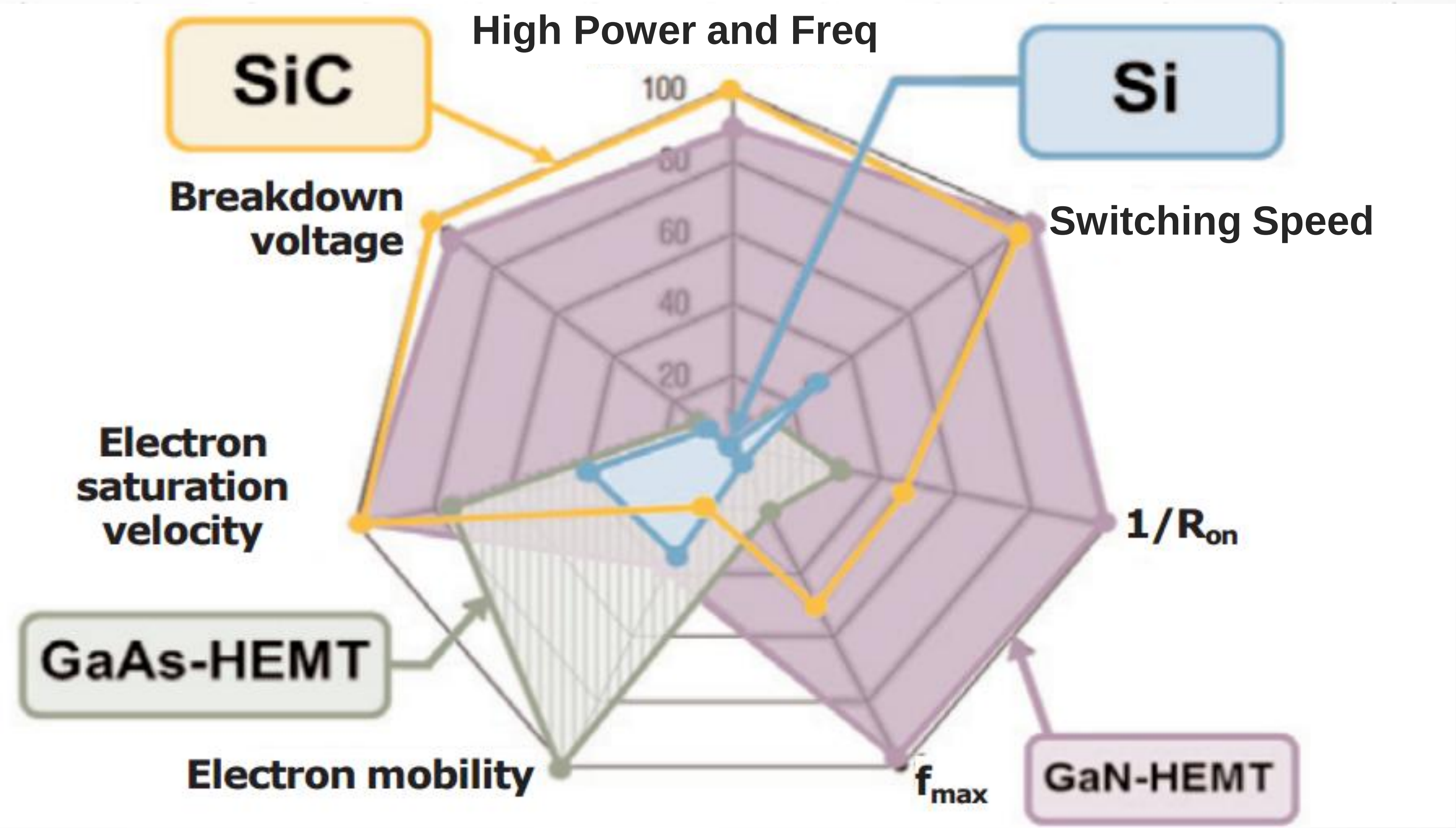
Source: "RF Power Market and Technologies 2017: GaN, GaAs and LDMOS" -www.i-micronews.com

Properties (at 300 K)	Units	Si	GaAs	4H-SiC	GaN
Bandgap Eg	eV	1.12	1.42	3.26	3.425
Breakdown electric field Ec	MV/cm	0.3	0.4	3	3.3
Intrinsic carrier concentration ni	cm^{-3}	9.6×10^{9}	1.5×10^{6}	8.2×10^{-9}	1.9×10^{-10}
Electron mobility μ_N	$cm^2/V/s$	1500 (bulk) 300 (inv)	8500	1000	1250 (bulk) 2000 (2DEG)
Saturation velocity vsat	$x10^7$ cm/s	1	2.5	2	2.2
Relative permittivity εr		11.8	13.1	10	9
Thermal conductivity λ	W*K/cm	1.5	0.43	4.9	1.3
Maximum working temperature Tmax	°C	150		760	800

GaN Material Properties

GaN RF Power Applications

High Electron Mobility Transistor (**HEMT**)

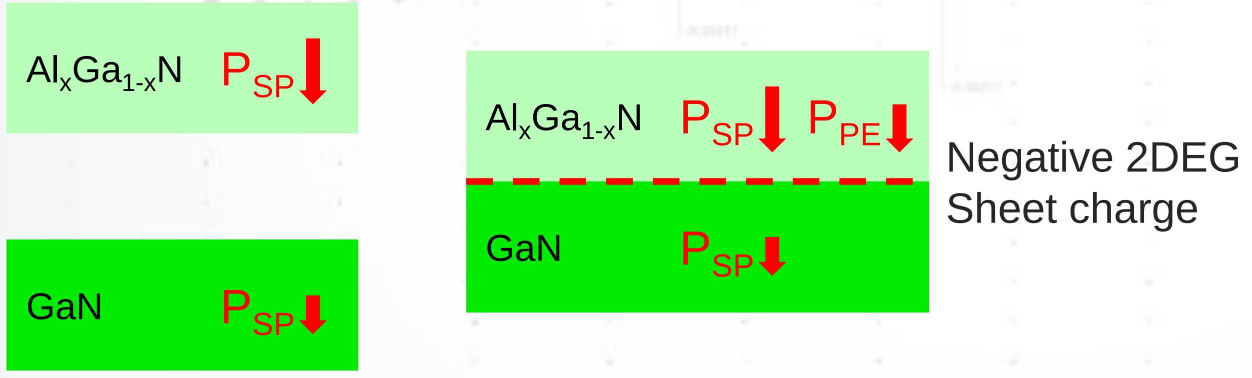


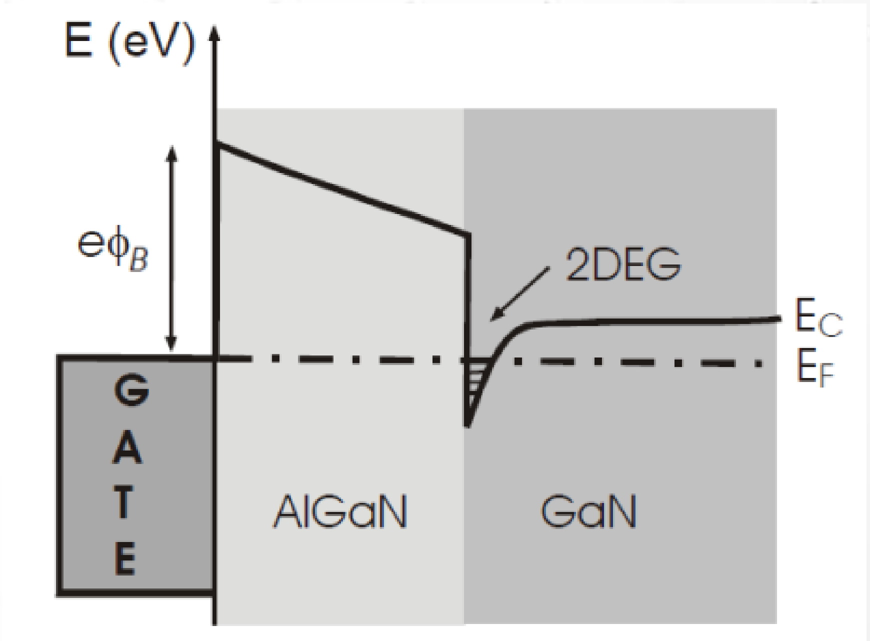
GaN HEMT Devices

HOW DOES A GAN DEVICE WORK?

- Difference between $Al_xGa_{1-x}N$ and GaN spontaneous polarization **(P_{SP})** creates a sheet charge at the interface.
- Difference in lattice constants leads to mechanical strain and piezoelectric effect **(P_{PE})**

- quantum well at the heterojunction interface → 2 Dimensional Electron Gas (2-DEG)
  - very high mobility
  - Low resistance

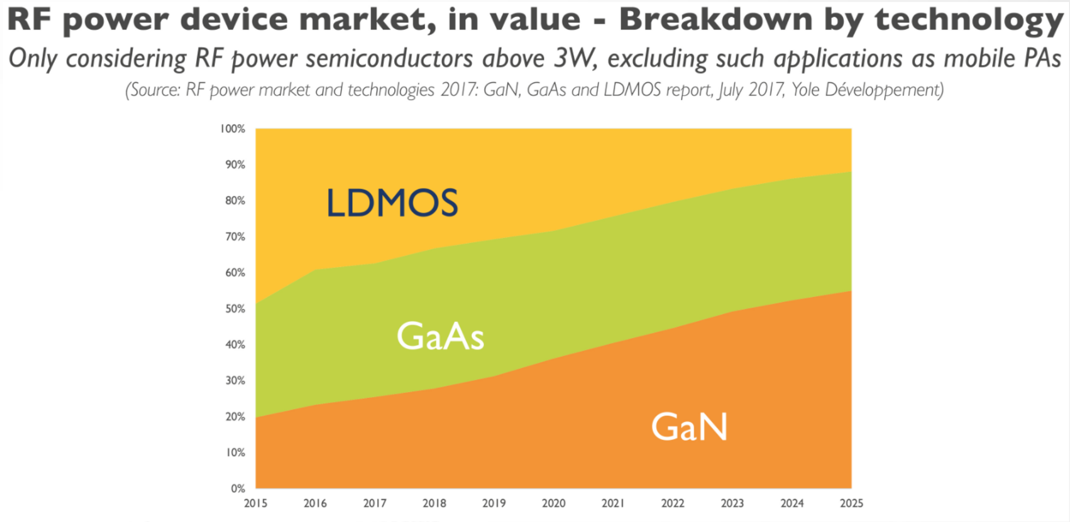


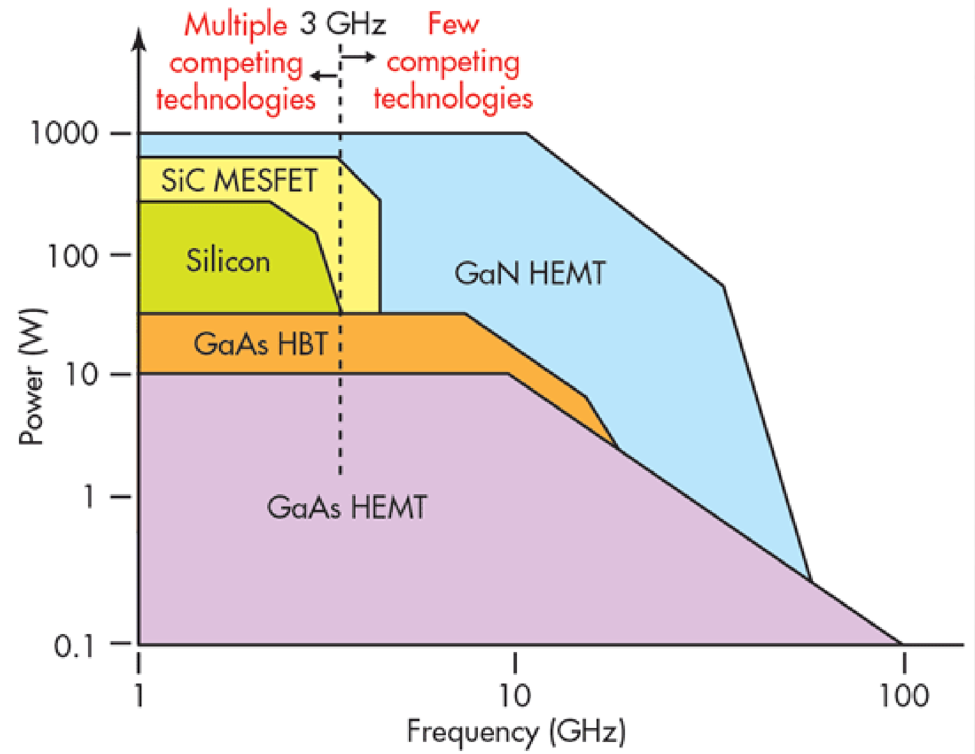


What's the Hold Up? Cost.

1. Silicon – gigantic history
2. High power applications:
   → LDMOS RF devices continue to improve
   → GaN is a competitor
3. Low power, low cost applications:
   → CMOS continues to rule.

GaN on Silicon on the horizon for lower power applications





GaN HEMT Devices

TECHNOLOGY OVERVIEW

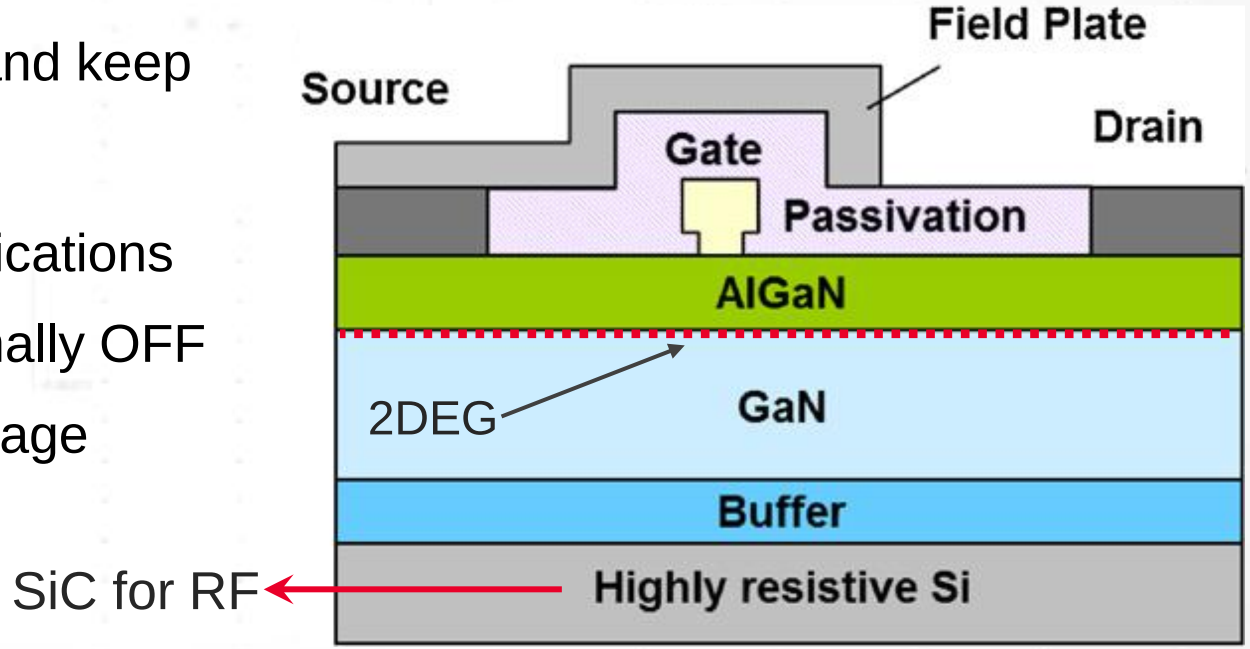
High mobility → RF applications

- SiC substrate to reduce substrate loss and keep device cool.

High breakdown → Power electronics applications

- P-GaN or cascode structure to get normally OFF
- Field plates for increase breakdown voltage

Typical structure of RF/Microwave GaN on Si HEMT*



Tetsuzo Ueda et al., Japanese Journal of applied Physics, 2014

Gallium-Nitride devices, technology and business drivers

Survey of GaN Models

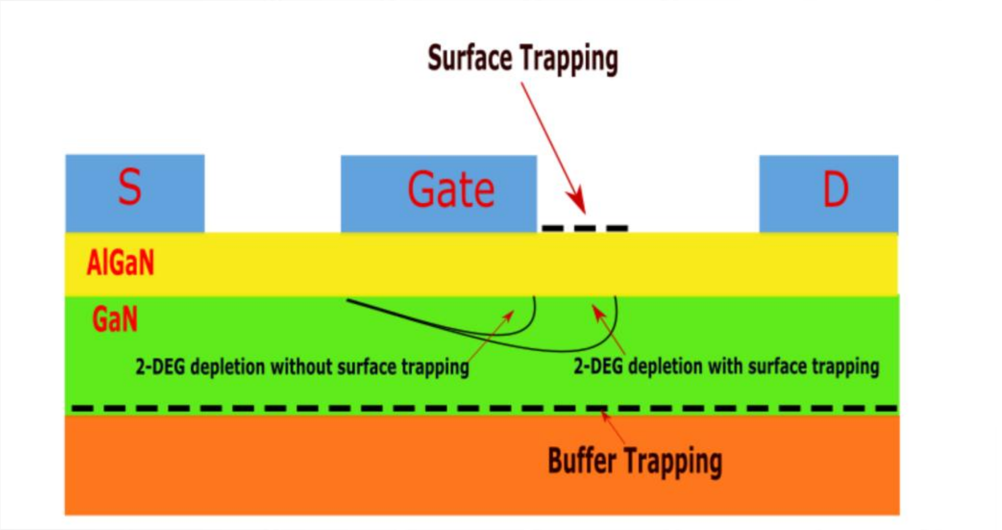
Core model descriptions:
Angelov-GaN, MVSG, ASM-HEMT and DynaFET models

Model parameter extraction

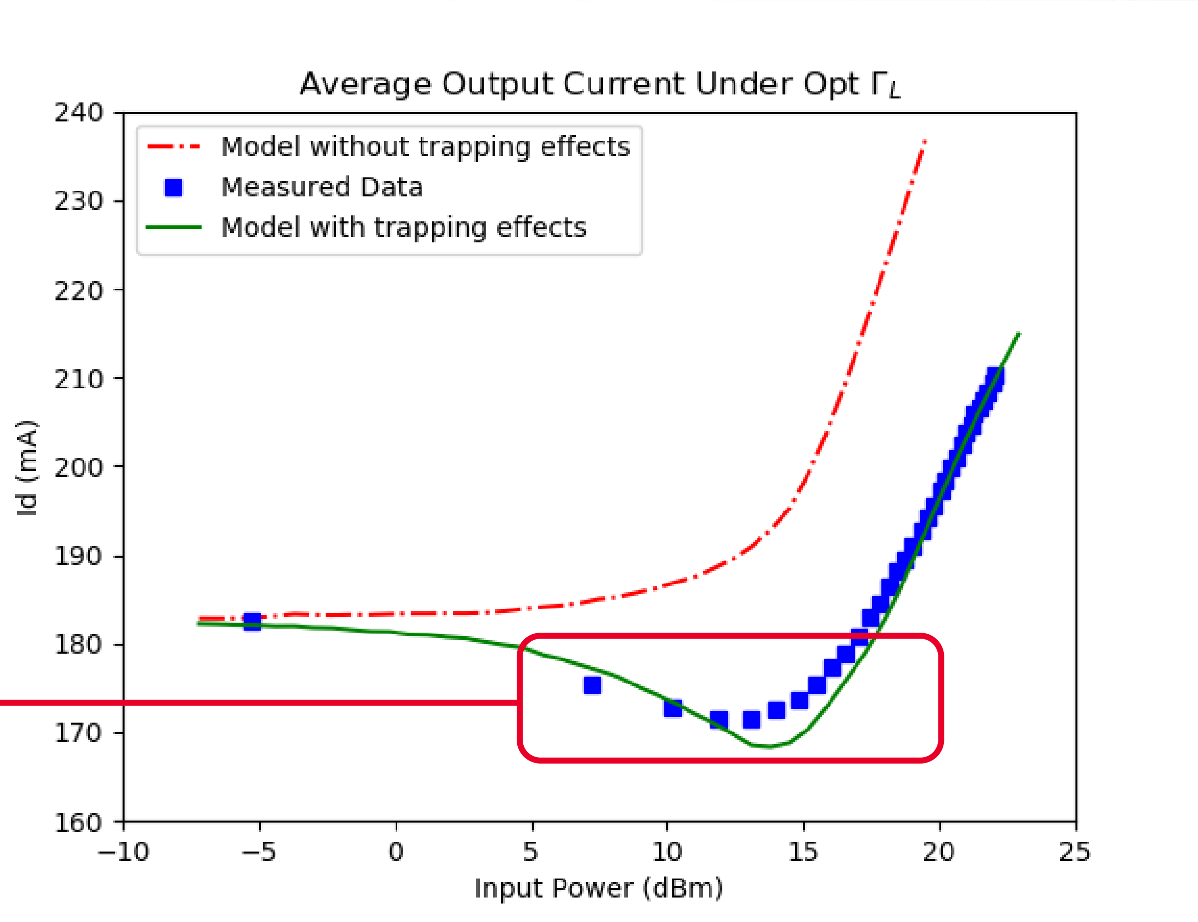
Using large signal measurements for more accurate parameter determination.

Modeling Challenges: Trapping and Current Collapse

Need Trap Models



Current collapse

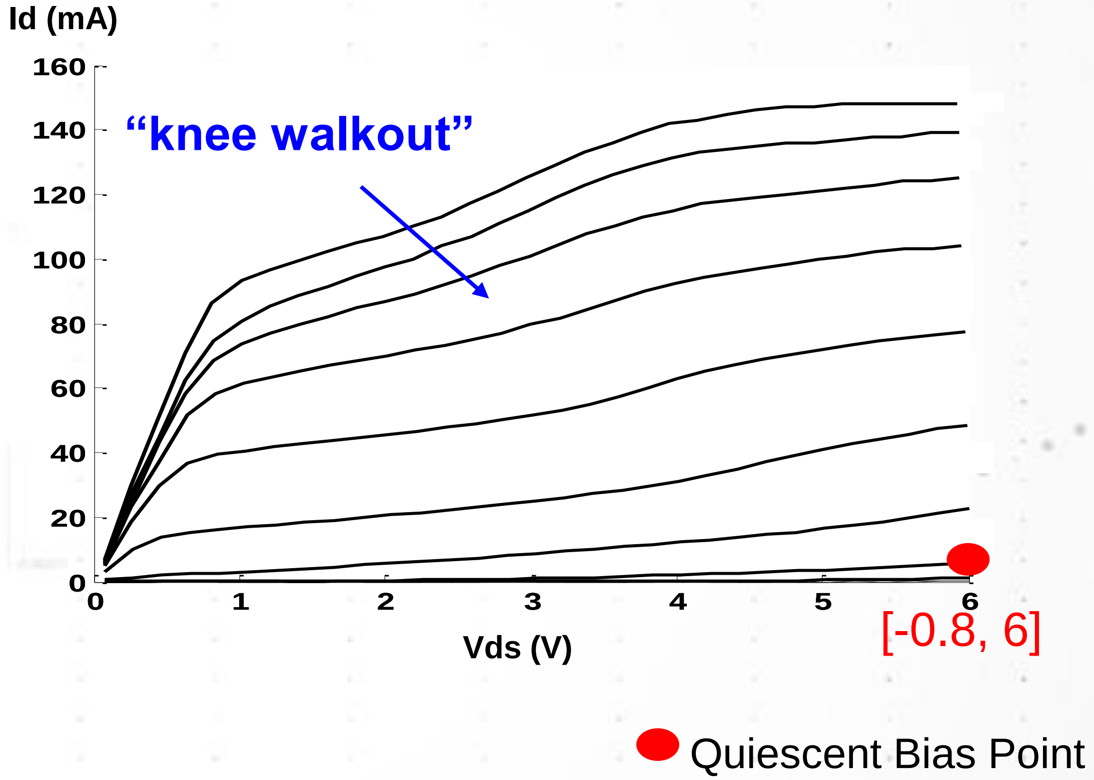


Agnihotri et al, INDICON 2015

Jardel, et al - "An Electrothermal Model for AlGaN/GaN Power HEMTs Including Trapping Effects to Improve Large-Signal Simulation Results on High VSWR", MTT, Dec 2007

Drain Lag

Pulsed IV measurements

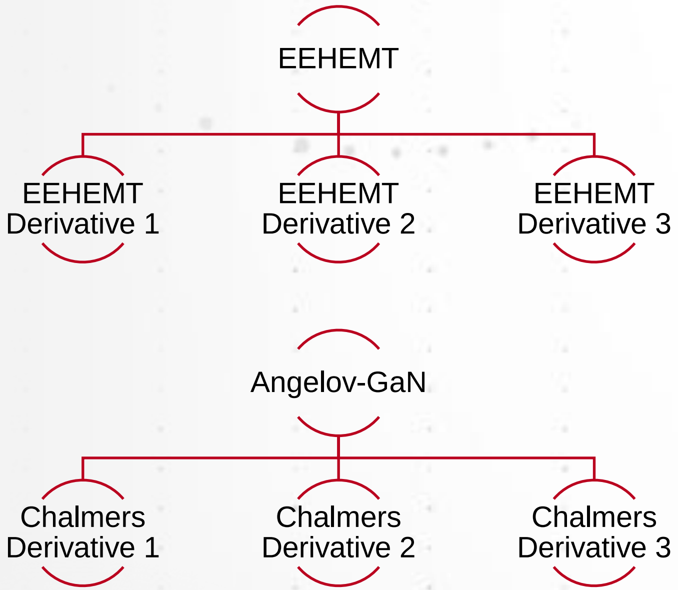


But:

- Which I-V curves to use?
- How to relate PIV curves to model coupling terms (trapping model)?

Available GaN Models

Model	Institute/Company	Authors	Year	Notes
EEHEMT	Agilent/Keysight	Eric Arnold	1998	empirical model, based evolution of EEFET model
Angelov	Chalmers Univ	Iltcho Angelov	1992	"A new empirical nonlinear model for HEMT and MESFET devices"
Angelov-GaN	Chalmers Univ	Iltcho Angelov	2008	extension of Angelov Model for GaN
DynaFET	Agilent/Keysight	Jianjun Xu, David Root et al.	2014	Uses data to train artificial neural network (ANN)
ASM-HEMT	Berkeley	S Khandelwal and Y Chauhan	2015	physics based surface potential model
MVSG	MIT	Ujwal Radhakrishna	2013	physics based virtual source model



DynaFET — Most accurate model

MVSG
ASM-HEMT

→ Accepted by Compact Model Coalition (CMC) in 2017

GaN Compact Model Comparison

	Empirical	Physics-based	ANN-based
Models	**Angelov-GaN, EEHEMT**	**ASM-HEMT MVSG**	**DynaFET**
CMC Standard		✓	
Scalable, W/L/NF	✓ *	✓	✓ *
Early availability during process development	✓		✓
Does not require process info	✓	*	✓
Simple extraction flow	✓		
Good DC/S-par fit	✓	✓	✓
Large signal across different bias		✓	✓
Simulation robustness		✓	✓

* limited

Gallium-Nitride devices, technology and business drivers

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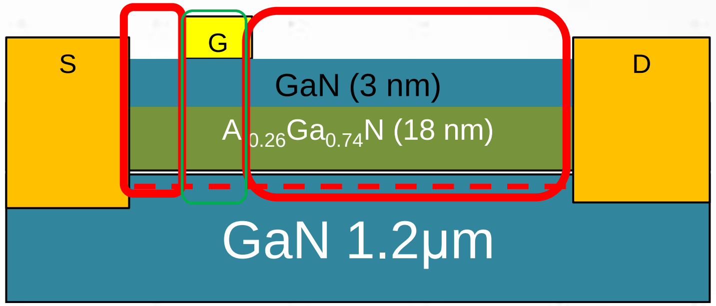
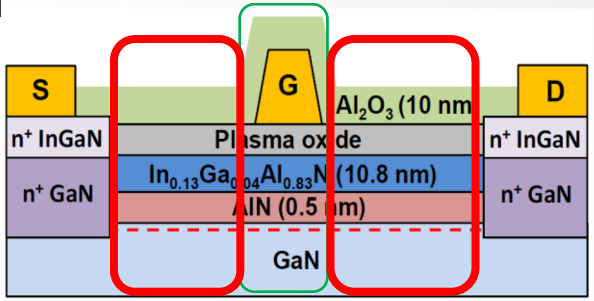
Model Overview



HV-GaN HEMT



RF-GaN HEMT

Field plates →

Substrate loss →

Short Channel Effects →

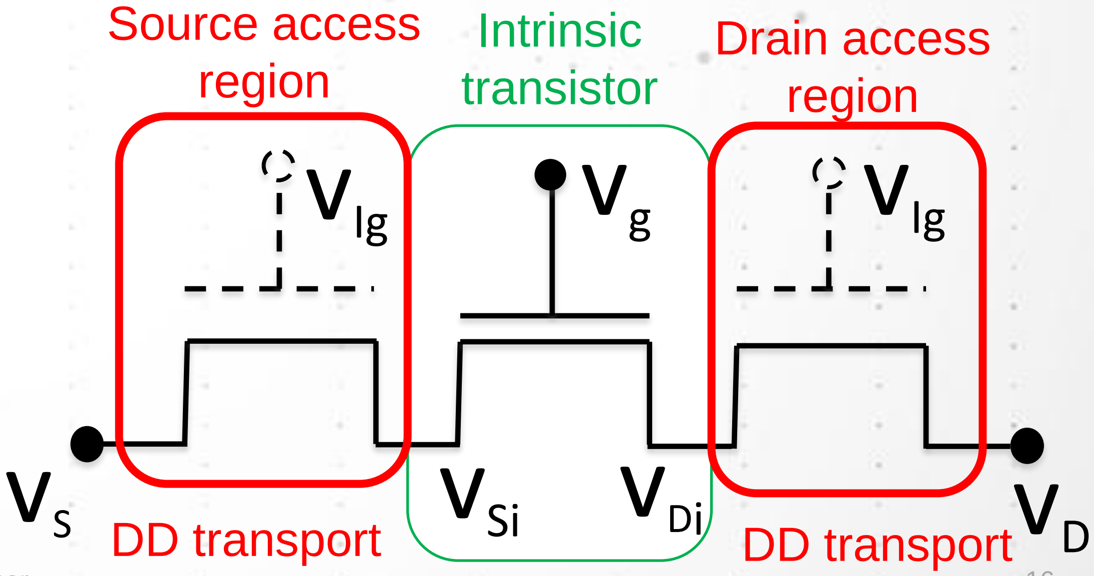
Mobility degradation →

Electrostatics →

Temp dependence/Self-heating →

Bias dep access region →

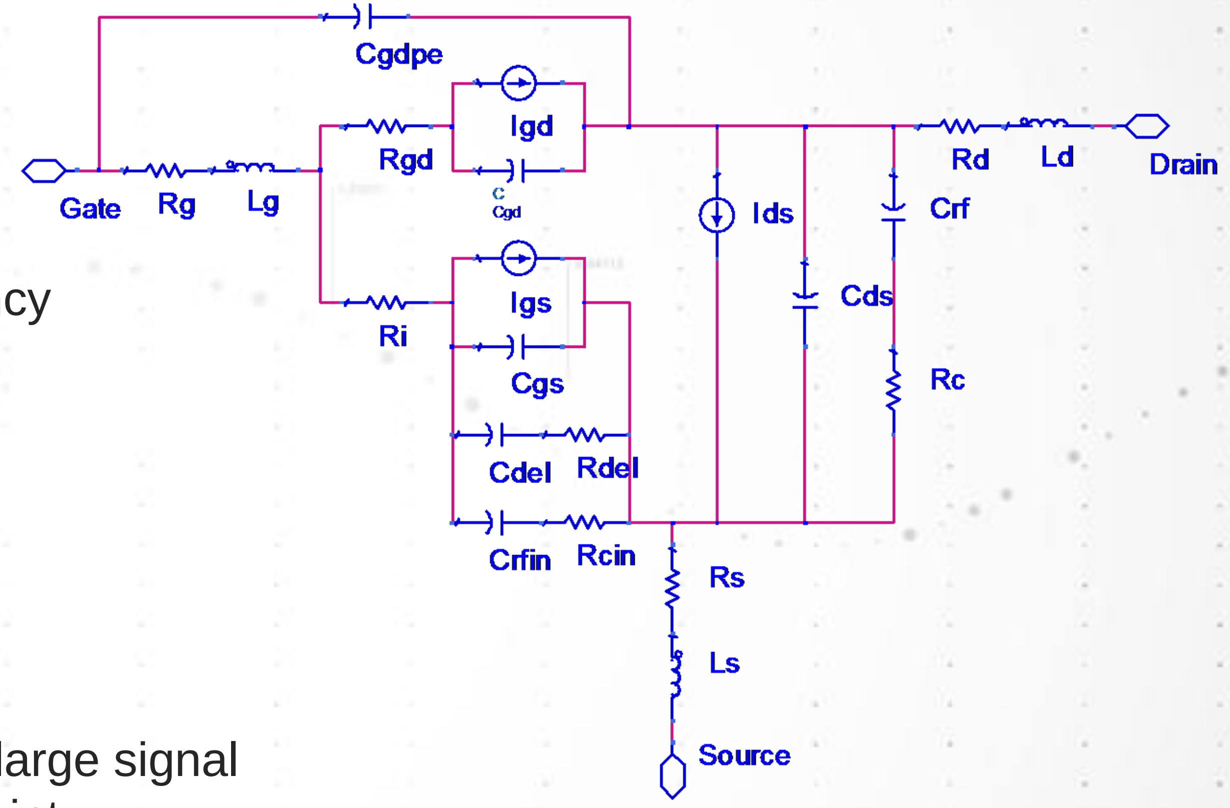
Core Drain Current Model



Source: Dr Ujwal Radhakrishna, MIT

Angelov GaN Model

EMPIRICAL MODEL



Updated to include better fits on harmonics, frequency dispersion, capacitance, etc.

Strengths:

- Simple extraction method
- Industry workhorse for 10+ years.

Limitations:

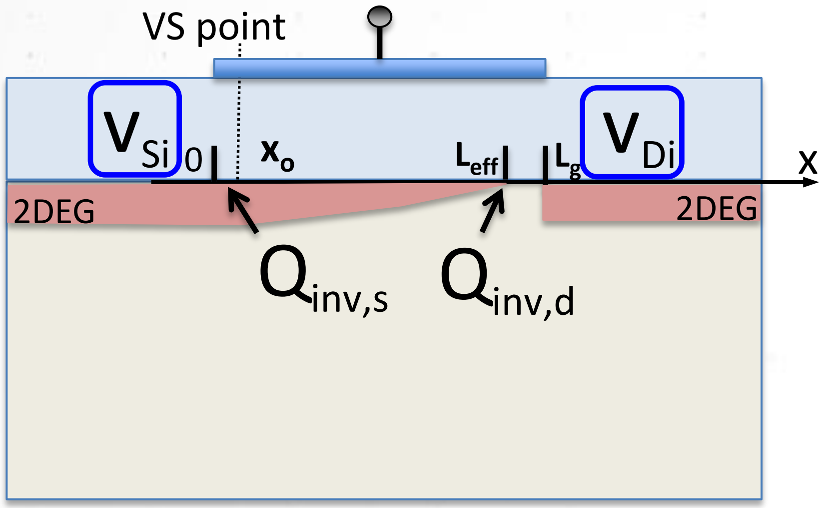
- Extracted from S-pars → might not work well for large signal
- Workaround - adapt model card for target bias point

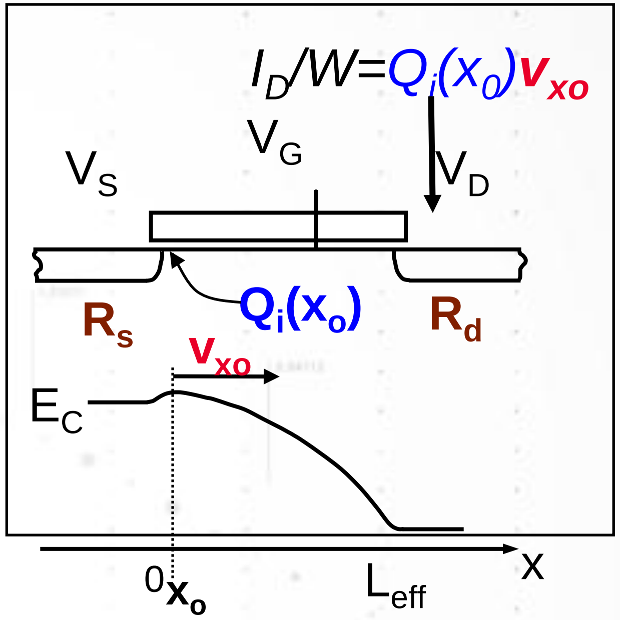
$$I_{ds} = I_{pk}(1+\tanh(y))(1+lV_{ds})\tanh(aV_{ds})$$

$$y = P_1(V_{gs} - V_{pk}) + P_2(V_{gs} - V_{pk})^2 + P_3(V_{gs} - V_{pk})^3$$

MIT Virtual Source GaN (MVSG) Model

Charge-based Physics Model





$$F_{Vsat} = \frac{\left(Q_{inv,s} - Q_{inv,d}\right)/C_g V_{DSAT}}{\left(1+\left(\left(Q_{inv,s} - Q_{inv,d}\right)/C_g V_{DSAT}\right)^b\right)^{1/b}}$$

$$Q_{inv,s} = C_g 2n\phi_t \ln\left(1+\exp\frac{\left(V_G - F_{sat}\boxed{V_{Si}}\right)-\left(V_T^* - \alpha\phi_t F_{f,s}\right)}{2n\phi_t}\right)$$

$$Q_{inv,d} = C_g 2n\phi_t \ln\left(1+\exp\frac{\left(V_G - F_{satd}\boxed{V_{Di}}\right)-\left(V_T^* - \alpha\phi_t F_{f,d}\right)}{2n\phi_t}\right)$$

Source and drain end charge

Saturation velocity

$$I_D / W = \boxed{v_{sat}} \frac{\boxed{\left(Q_{inv,s} + Q_{inv,d}\right)}}{2} \boxed{F_{Vsat}}$$

Function for transition from non-velocity-saturation to vel sat

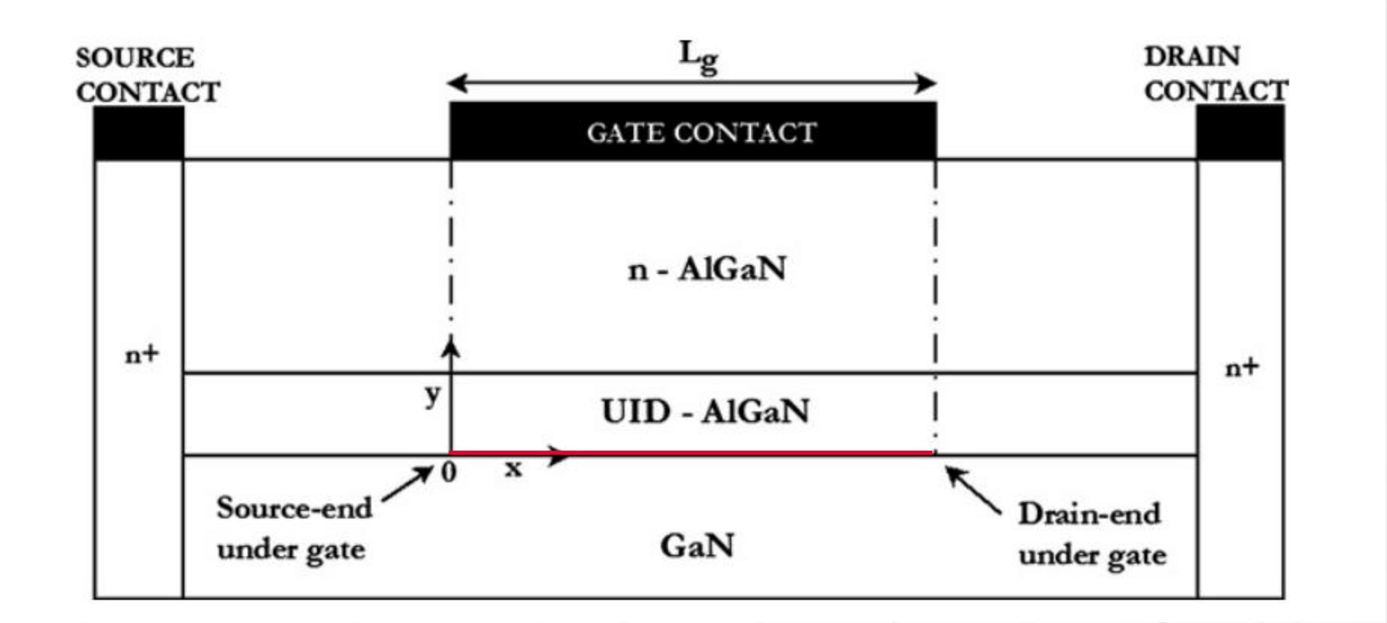
Source: Dr Ujwal Radhakrishna, MIT

ASM-HEMT Model

Surface Potential Physics Model

ψ = Surface potential along the 2DEG
Solve for ψ and charge on the channel

Derive unified expression for Id(Vgs, Vds)



Velocity Saturation

Short Channel Effects

2DEG Charge

Fermi Level

Surface Potential

Capacitance

Channel Length Modulation

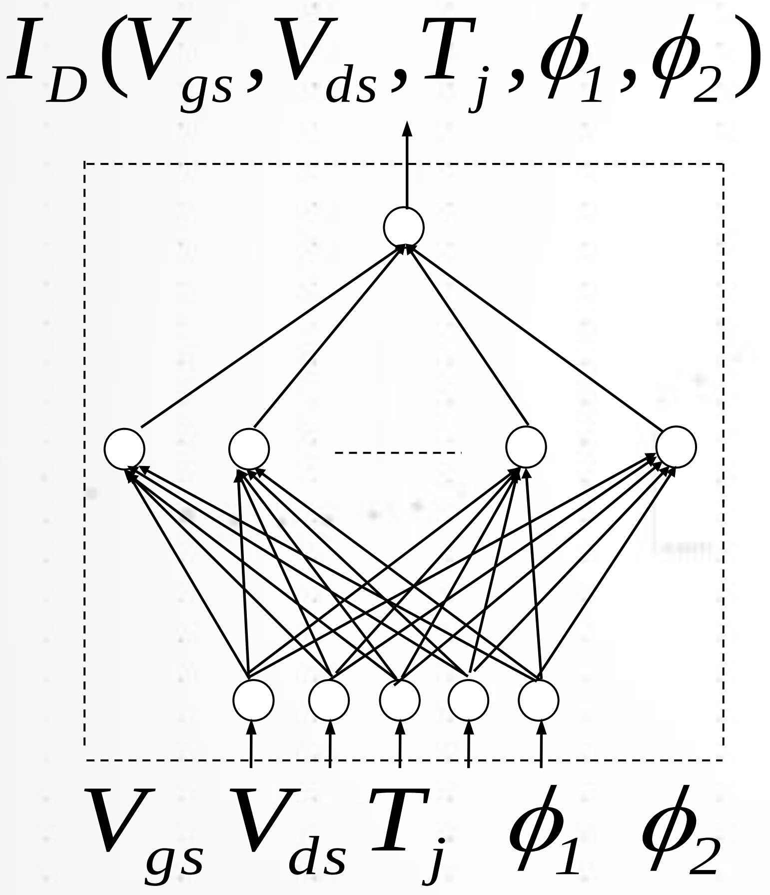
Self-Heating Effects

$$I_d = \frac{\mu_{eff}}{\sqrt{1 + \theta_{sat}{}^2 \psi_{ds}^2}} \frac{W}{L} C_g N_f \left[V_{go} - \left(\frac{\psi_s + \psi_d}{2} \right) + V_{th} \right] \psi_{ds}$$

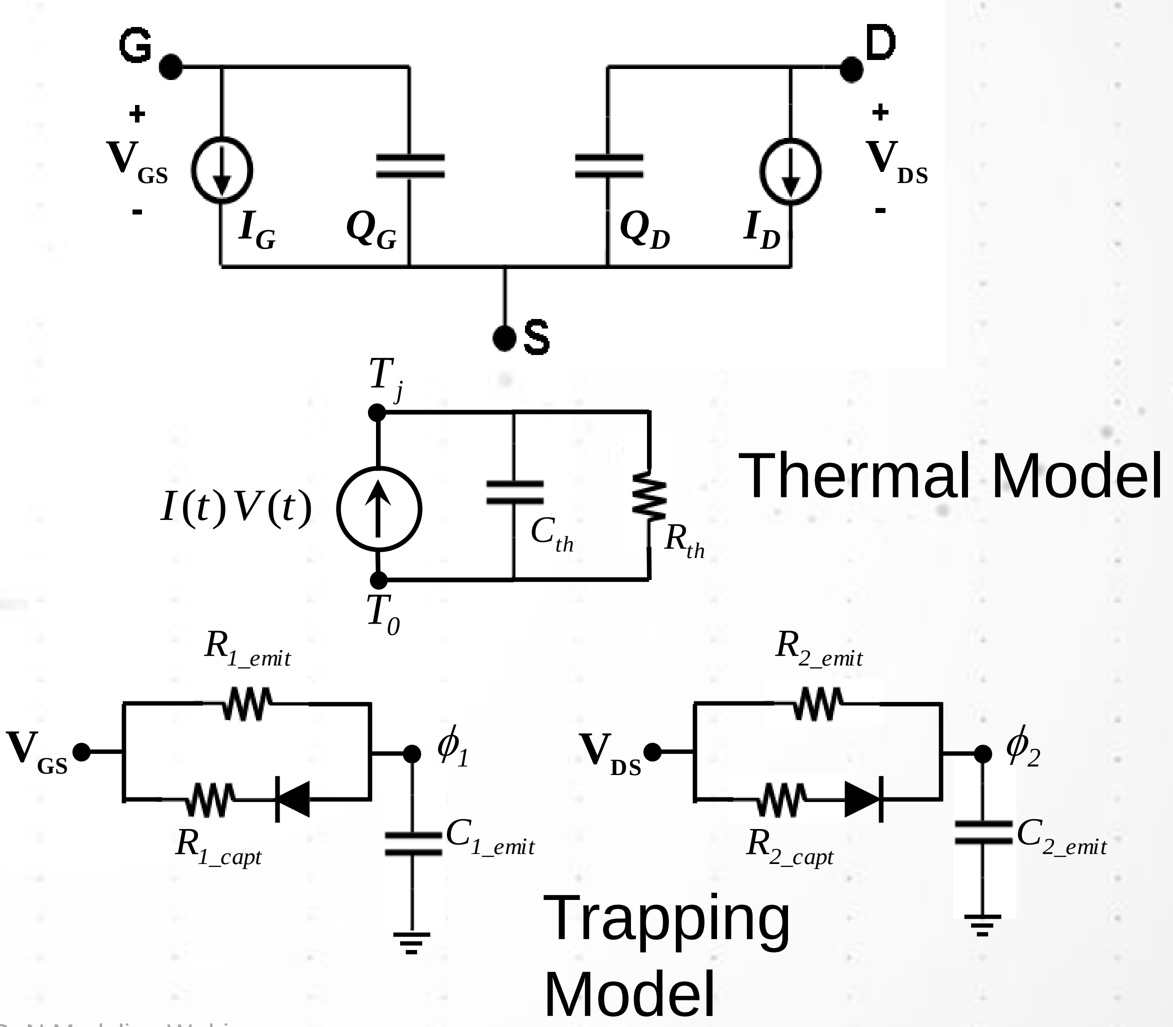
Dasgupta, Ghosh, Chauhan and Khandelwal, "ASM-HEMT: Compact model for GaN HEMTs", IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), June 2015

The DynaFET Model

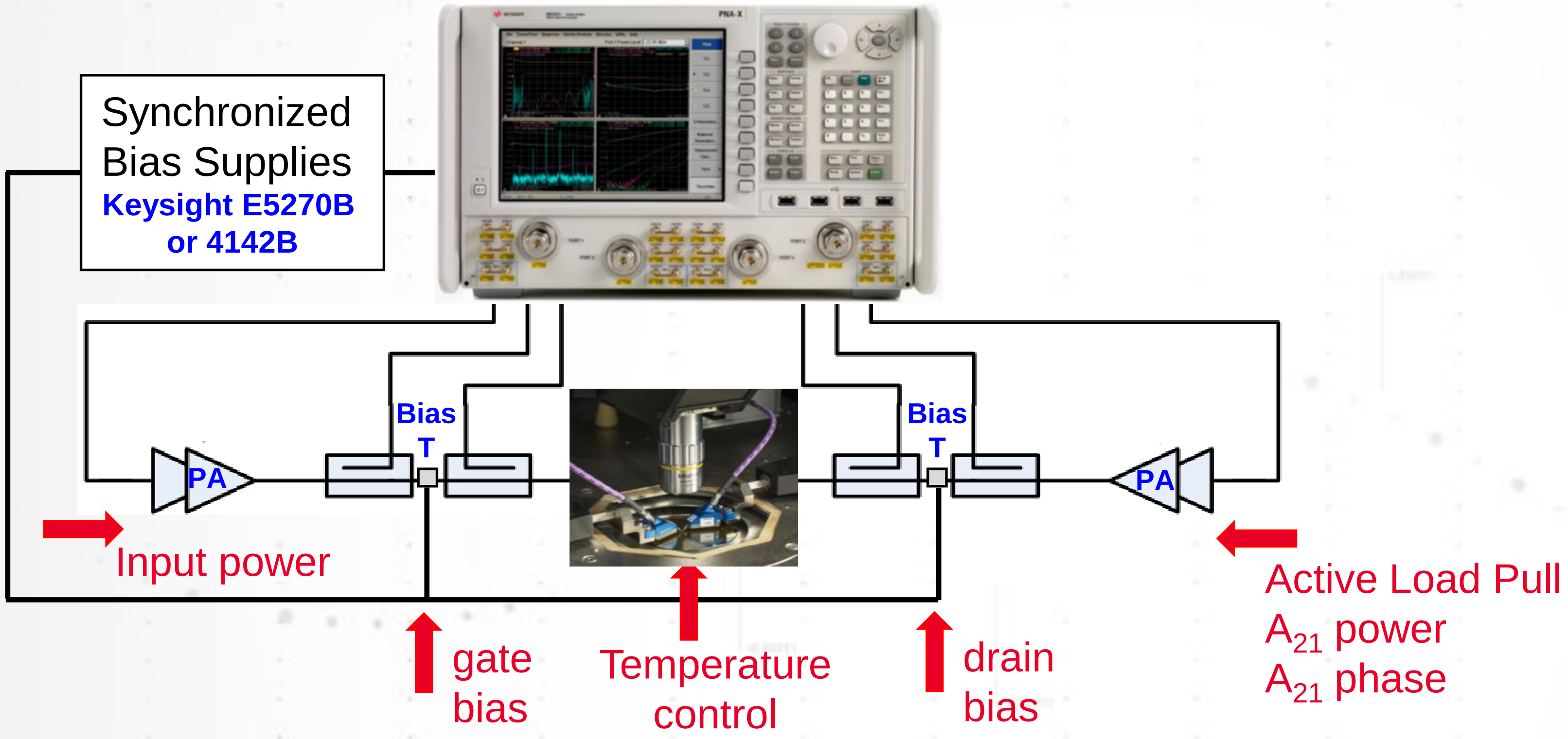
DYNAMIC SELF-HEATING, TRAPPING, ANN



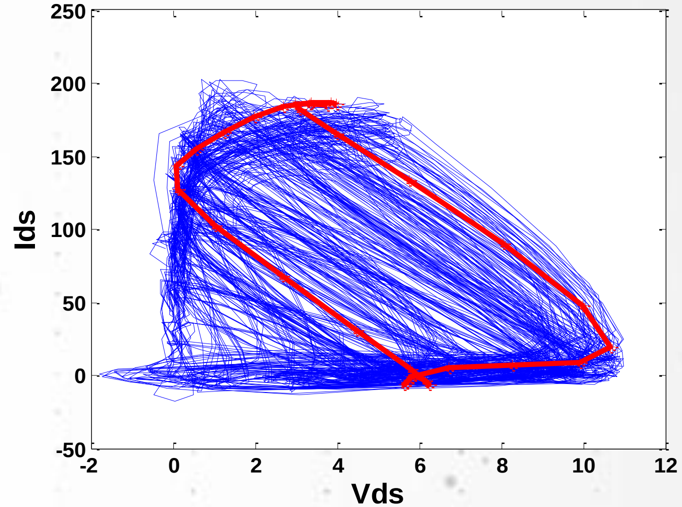
Artificial Neural Network



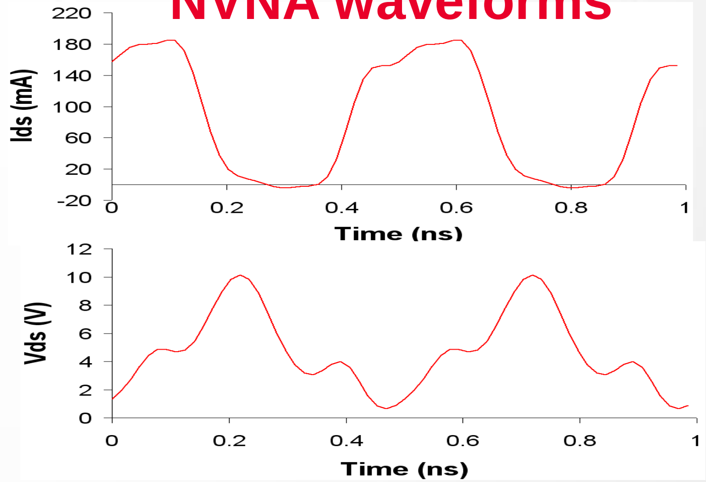
Active Source Injection Setup



Dynamic Load-lines



NVNA waveforms



DynaFET characterization performed at various:

(1) DC biases

(2) Input powers

(3) Load Impedances, magnitude and phase

(4) Ambient temperatures

(5) Fundamental frequency + 20 harmonics

Gallium-Nitride devices, technology and business drivers

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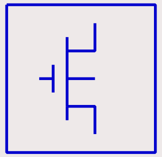
Lots of Parameters



ASM_HEMT_M
Eguchi_6_6_2018

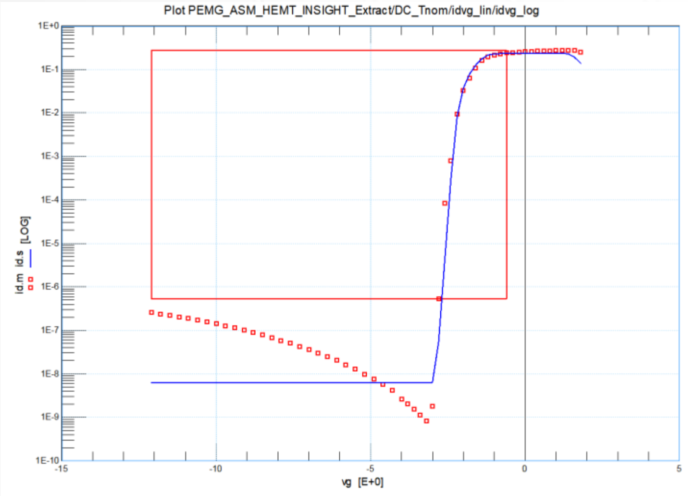
tnom=27.00	eta0= 90.08m	ns0accd= 3.245E+17	krsc= 3.388m	atrapeta0= 0.000	rontr2= 100.0f	iminfp1= 1.000f
tbar= 8.044n	vdscale= 5.549	k0accs= 0.000	krdc= 2.951m	btrapeta0= 50.00m	rontr3= 100.0f	vofffp1=-25.00
l=0.25u	kt1= 100.0m	k0accd= 0.000	gatemod= 1.000	atraprs= 100.0m	rtrap3= 1.000	dfp1= 50.00n
w=100u	thesat= 1.000	u0accs= 218.8m	njgs= 12.50	btraprs= 600.0m	ctrap3= 100.0u	lfp1= 1.000u
nf=8	nfactor= 772.7m	u0accd= 2.032	njgd= 2.500	atraprd= 500.0m	vatrap= 10.00	ktfp1= 50.00m
epsilon=37.31p	cdscd= 1.921m	mexpaccs= 2.000	igsdio= 2.416	btraprd= 600.0m	wd= 16.00m	u0fp1= 100.0m
voff=-1.996	gamma0i= 2.120p	mexpaccd= 2.000	igddio= 11.19	rtrap1= 1.000	vdlr1= 2.000	vsatfp1= 100.0K
u0= 932.2m	gamma1i= 3.730p	lsg= 1.000u	ktgs= 0.000	rtrap2= 1.000	vdlr2= 20.00	nfactorfp1= 500.0m
ua= 1.000p	imin= 1.000n	ldg= 1.600u	ktgd= 0.000	ctrap1= 10.00u	talpha= 1.000	cdscdfp1= 0.000
ub= 1.000a	shmod=	rsc= 356.5u	trapmod= 0.000	ctrap2= 1.000u	vtb= 250.0	eta0fp1= 1.000n
vsat= 105.4K	rth0= 12.59	rdc= 2.333m	cdlag= 1.000u	a1= 100.0m	deltax= 10.00m	vdscalefp1= 10.00
delta= 2.000	cth0= 1.000n	kns0= 12.02m	rdlag= 1.000MEG	vofftr= 1.000n	fp1mod= 0.000	gamma0fp1= 2.120p
at= 54.95m	rdsmod= 1.000	ats=-199.5m	idio= 1.000	cdscdtr= 1.000f	fp2mod= 0.000	gamma1fp1= 3.730p
ute=-165.3m	vsataccs= 122.4K	utes=-2.972	atrapvoff= 100.0m	eta0tr= 1.000f	fp3mod= 0.000	iminfp2= 1.000f
lambda= 258.8u	ns0accs= 4.719E+16	uted=-1.064	btrapvoff= 300.0m	rontr1= 1.000p	fp4mod= 0.000	vofffp2=-50.00

dfp2= 100.0n	ktfp3= 50.00m	vsatfp4= 100.0K	cfg= 17.78f	qm0i= 1.000m	cfp3scale= 0.000	noic= 0.000
lfp2= 1.000u	u0fp3= 100.0m	nfactorfp4= 500.0m	cfd= 27.54f	adosfp1= 0.000	cfp4scale= 0.000	ef= 1.000
ktfp2= 50.00m	vsatfp3= 100.0K	cdscdfp4= 0.000	cfgd= 87.10f	bdosfp1= 1.000	csubscalei= 0.000	tnsc= 1.000E+27
u0fp2= 100.0m	nfactorfp3= 500.0m	eta0fp4= 1.000n	cfgdsm= 1.000E-25	qm0fp1= 1.000m	csubscale1= 0.000	gdsmin= 1.000p
vsatfp2= 100.0K	cdscdfp3= 0.000	vdscalefp4= 10.00	cfgd0= 100.0p	adosfp2= 0.000	csubscale2= 0.000	
nfactorfp2= 500.0m	eta0fp3= 1.000n	gamma0fp4= 2.120p	cj0= 16.23f	bdosfp2= 1.000	csubscale3= 0.000	
cdscdfp2= 0.000	vdscalefp3= 10.00	gamma1fp4= 3.730p	vbi= 1.377	qm0fp2= 1.000m	csubscale4= 0.000	
eta0fp2= 1.000n	gamma0fp3= 2.120p	cgso= 499.8f	ktvbi= 0.000	adosfp3= 0.000	rgatemod= 0.000	
vdscalefp2= 10.00	gamma1fp3= 3.730p	cgdo=100e-15 {t}	ktcfg= 0.000	bdosfp3= 1.000	xgw= 0.000	
gamma0fp2= 2.120p	iminfp4= 1.000f	cdso=214.2f	ktcfgd= 0.000	qm0fp3= 1.000m	ngcon= 1.000	
gamma1fp2= 3.730p	vofffp4=-100.0	cgdl= 1.904f	mz= 500.0m	adosfp4= 0.000	rshg= 1.000m	
iminfp3= 1.000f	dfp4= 200.0n	vdsatcv= 100.0	aj= 800.0m	bdosfp4= 1.000	fnmod= 0.000	
vofffp3=-75.00	lfp4= 1.000u	cbdo= 0.000	dj= 60.00	qm0fp4= 1.000m	tnmod= 0.000	
dfp3= 150.0n	ktfp4= 50.00m	cbso= 0.000	adosi= 0.000	cfp1scale= 0.000	noia= 15.00p	
lfp3= 1.000u	u0fp4= 100.0m	cbgo= 0.000	bdosi= 1.000	cfp2scale= 0.000	noib= 0.000	

High Level Extraction Flow

DC

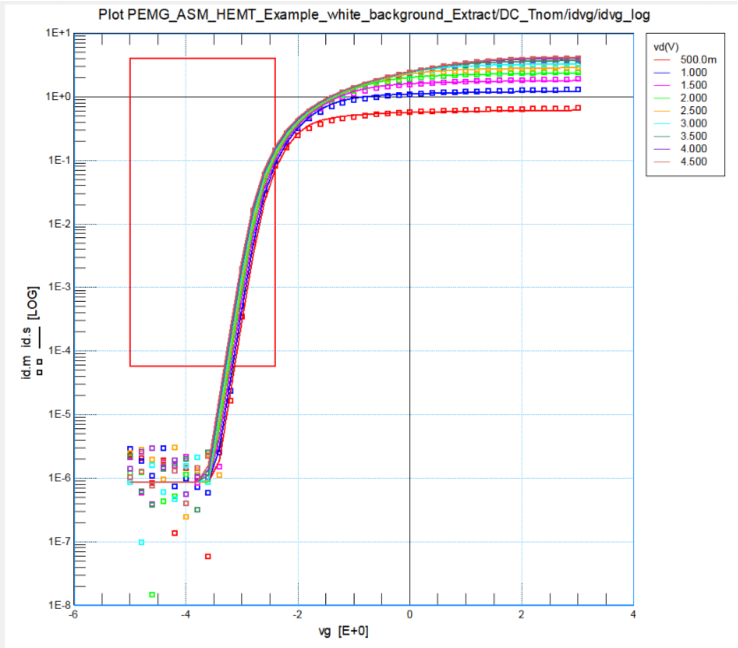
1) Linear Condition IdVg at low Vds



Params:

- VOFF, NFACTOR
- U0, UA, UB

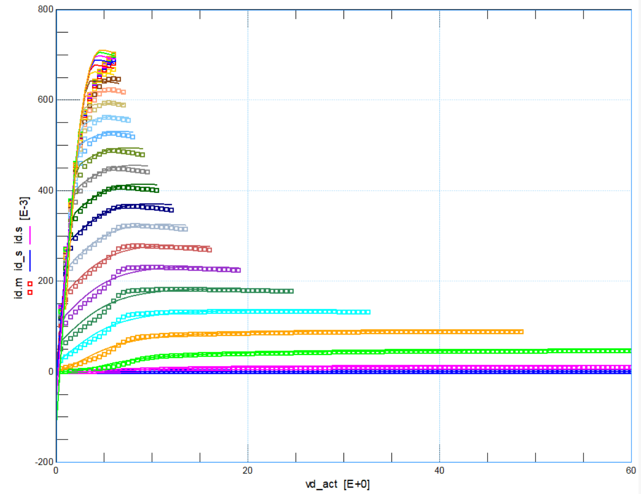
2) IdVg at high Vds



Params:

- ETA0, CDSCD, VSAT, VSATACCS
- NS0ACCS, NS0ACCD
- VDSCALE, VOFF (again)

3) Full Output Curves



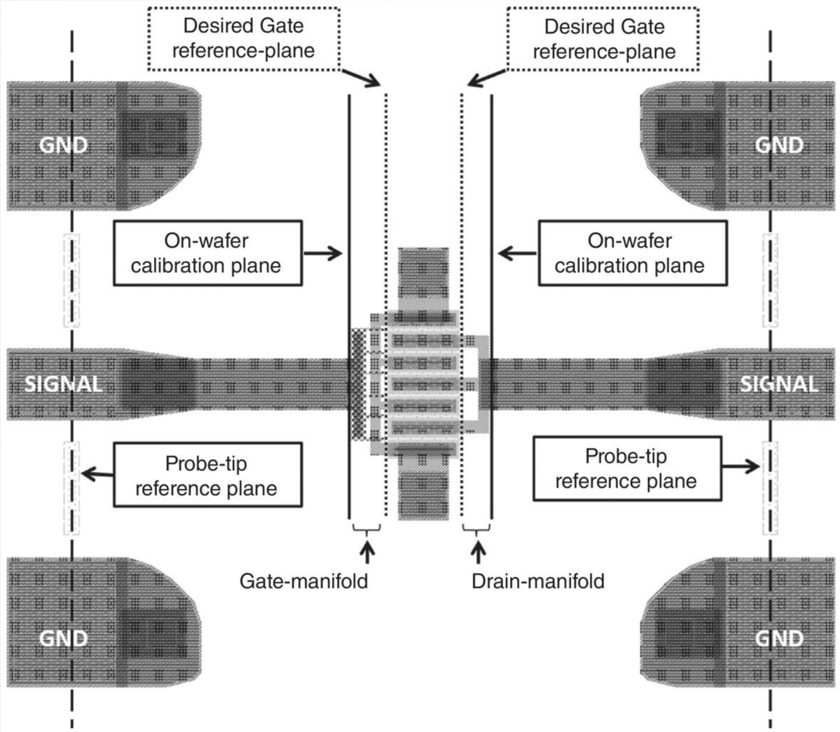
Params:

- LAMBDA, RSC, RDC
- RTH0, UTE, AT, KT1

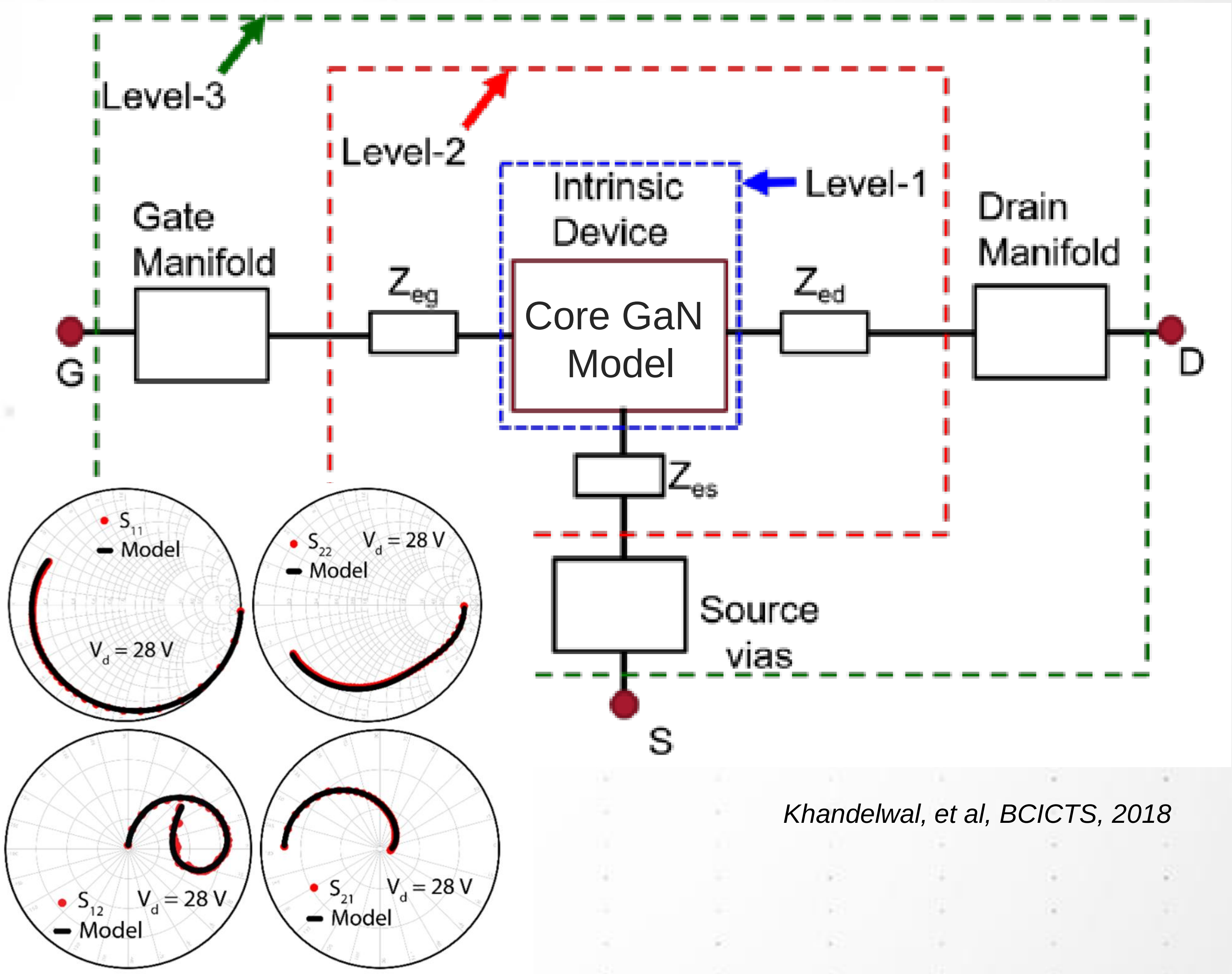
Khandelwal, et al, BCICTS, 2018

High Level Extraction Flow, part 2

RF

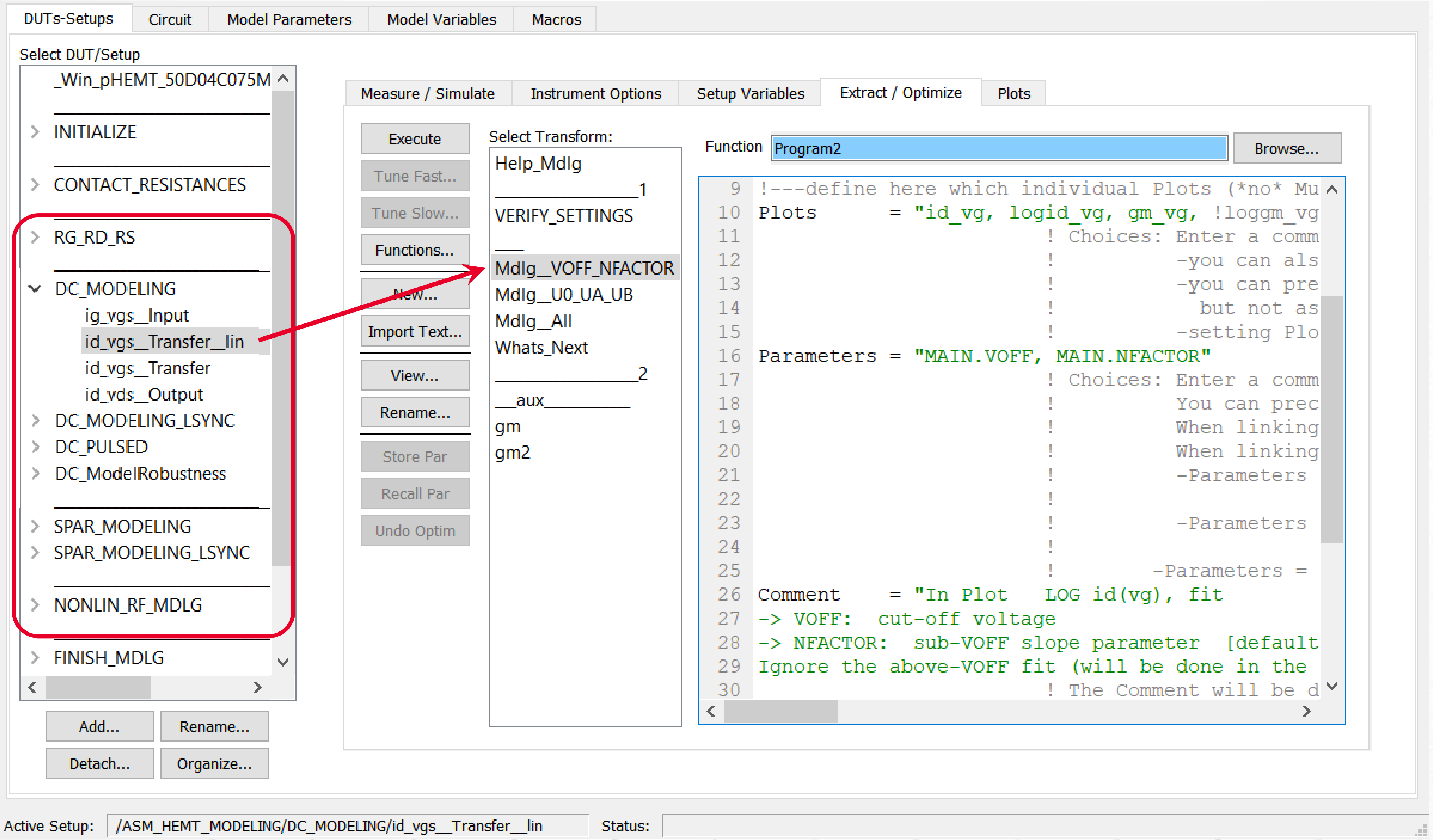


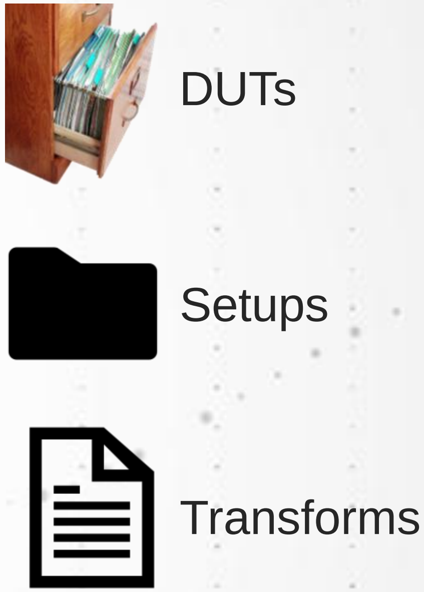
Nonlinear Circuit Simulation and Modeling, Cambridge University press

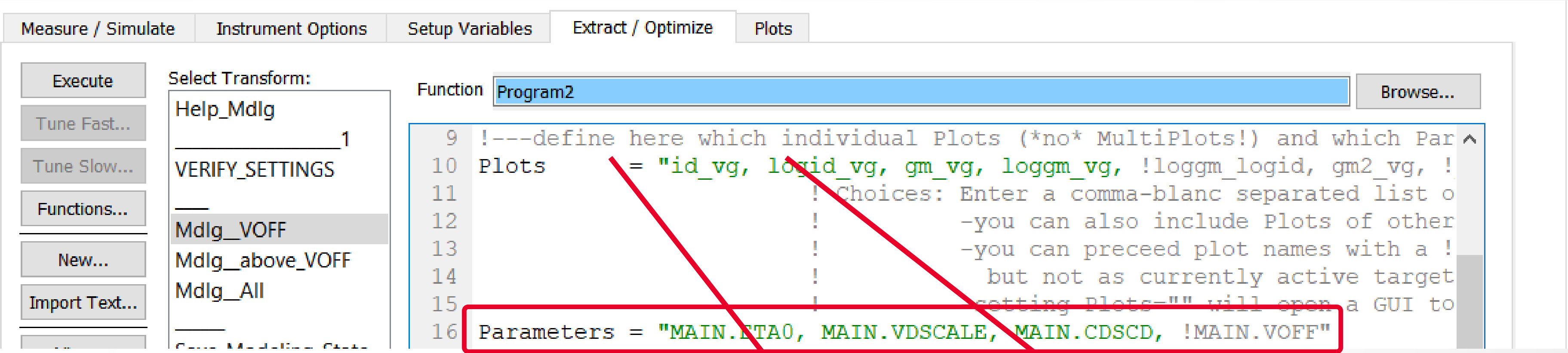


Khandelwal, et al, BCICTS, 2018

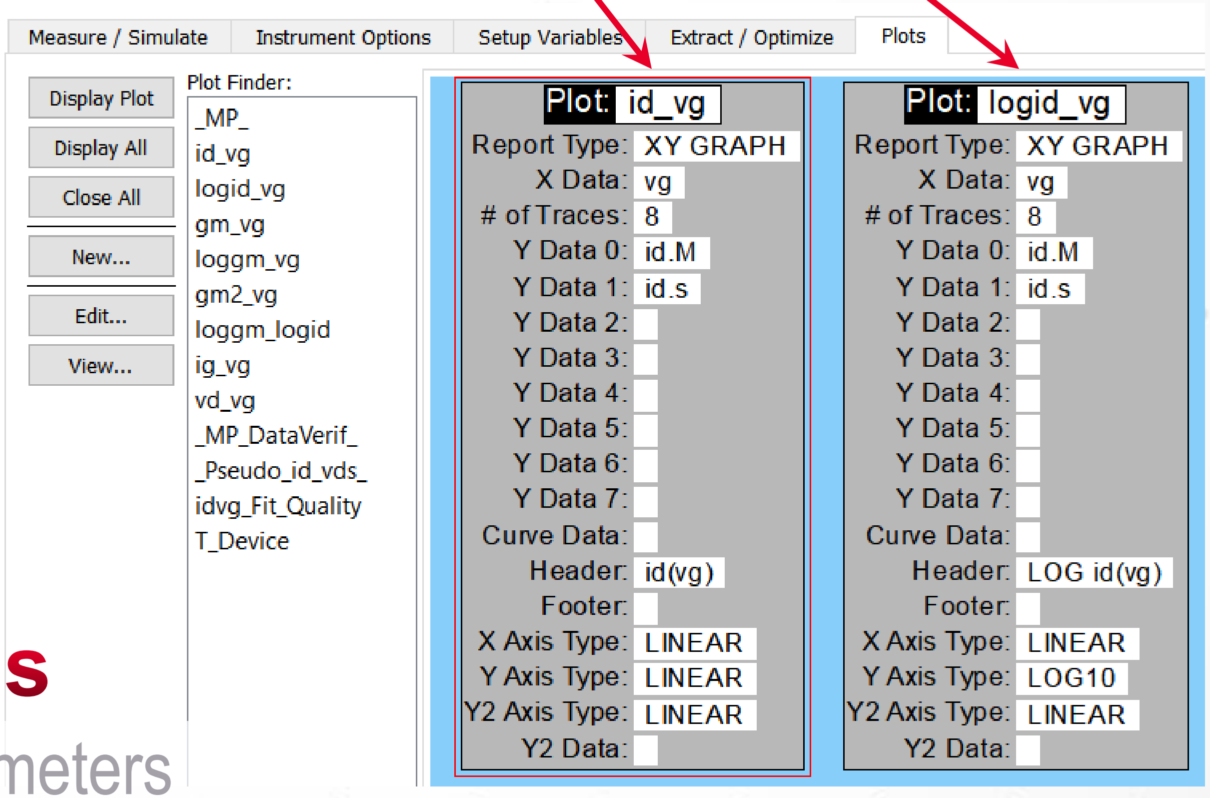
IC-CAP – DUTS/Setups/Transforms





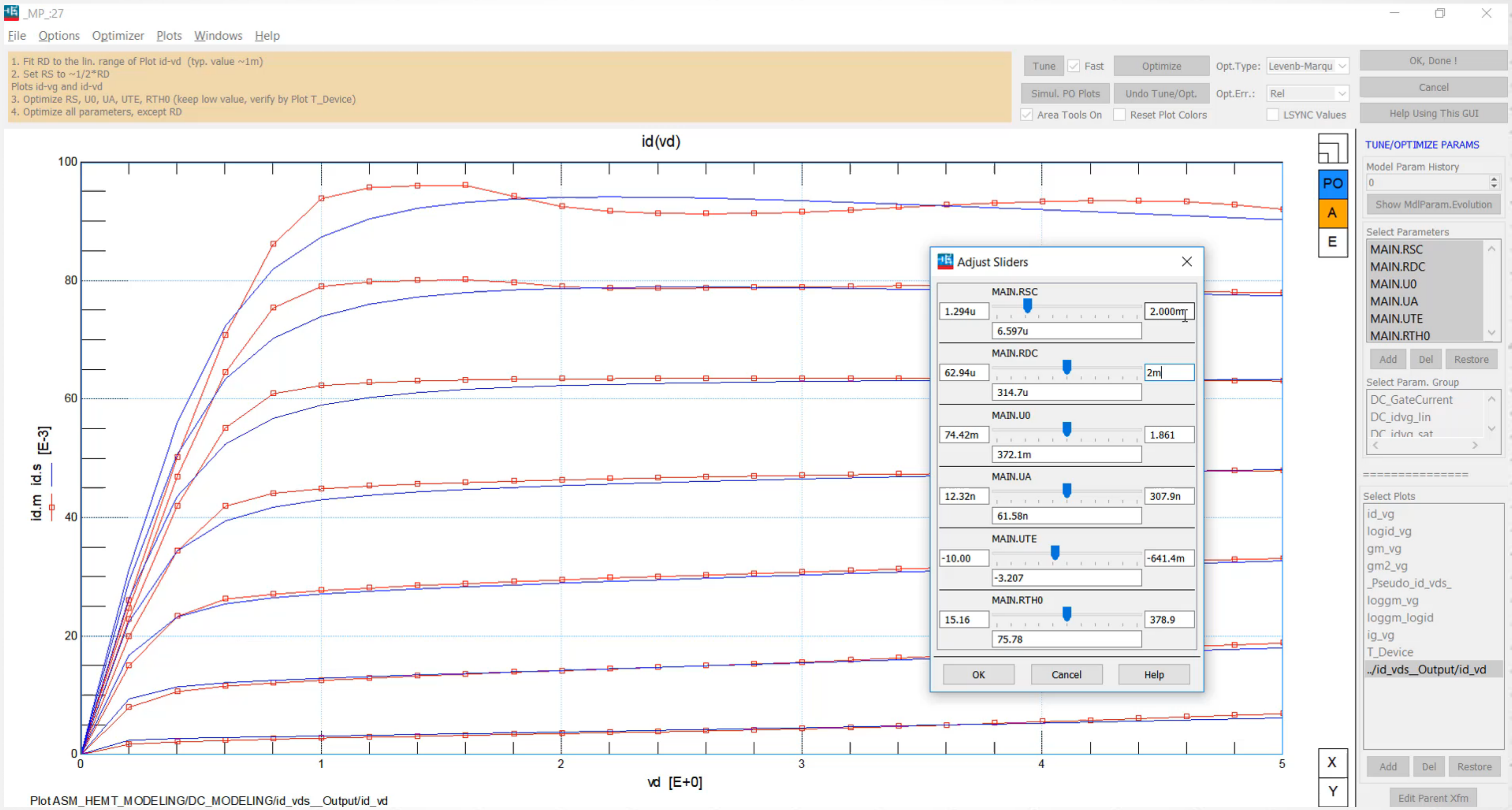


- Extraction
- Tuning
- Optimization



IC-CAP – Transforms

Choose plots + relevant parameters



_MP_:27
File Options Optimizer Plots Windows Help
1. Fit RD to the lin. range of Plot id-vd (typ. value ~1m)
2. Set RS to ~1/2*RD
Plots id-vg and id-vd
3. Optimize RS, U0, UA, UTE, RTH0 (keep low value, verify by Plot T_Device)
4. Optimize all parameters, except RD
Tune
Fast
Optimize
Opt.Type:
Levenb-Marqu
OK, Done !
Simul. PO Plots
Undo Tune/Opt.
Opt.Err.:
Rel
Cancel
Area Tools On
Reset Plot Colors
LSYNC Values
Help Using This GUI
id(vd)
id.m id.s [E-3]
vd [E+0]
Plot ASM_HEMT_MODELING/DC_MODELING/id_vds__Output/id_vd
PO
A
E
X
Y
Adjust Sliders
MAIN.RSC
1.294u
2.000m
6.597u
MAIN.RDC
62.94u
2m
314.7u
MAIN.U0
74.42m
1.861
372.1m
MAIN.UA
12.32n
307.9n
61.58n
MAIN.UTE
-10.00
-641.4m
-3.207
MAIN.RTH0
15.16
378.9
75.78
OK
Cancel
Help
TUNE/OPTIMIZE PARAMS
Model Param History
0
Show MdlParam.Evolution
Select Parameters
MAIN.RSC
MAIN.RDC
MAIN.U0
MAIN.UA
MAIN.UTE
MAIN.RTH0
Add
Del
Restore
Select Param. Group
DC_GateCurrent
DC_idvg_lin
DC_idvg_sat
Select Plots
id_vg
logid_vg
gm_vg
gm2_vg
_Pseudo_id_vds_
loggm_vg
loggm_logid
ig_vg
T_Device
../id_vds_Output/id_vd
Add
Del
Restore
Edit Parent Xfm

Gallium-Nitride devices, technology and business drivers

GaN model survey

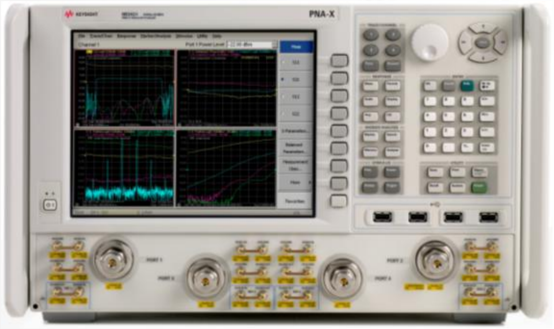
Core model descriptions:
Angelov-GaN, MVSG, ASM-HEMT and DynaFET models

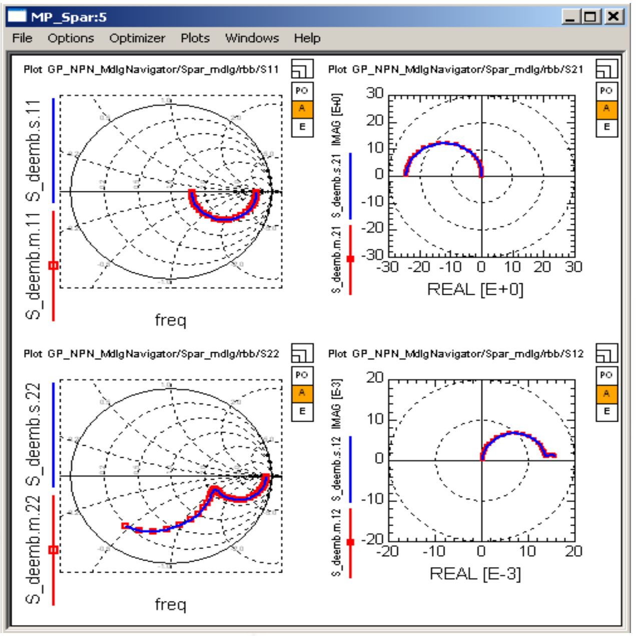
Model parameter extraction

Using large signal measurements for more accurate parameter determination

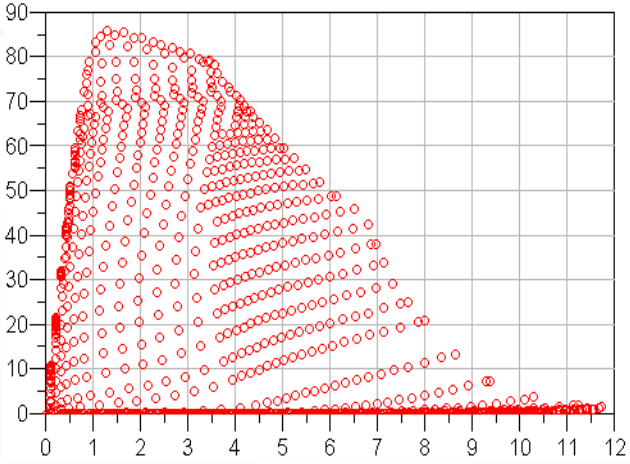
Conventional Device Modeling Flow

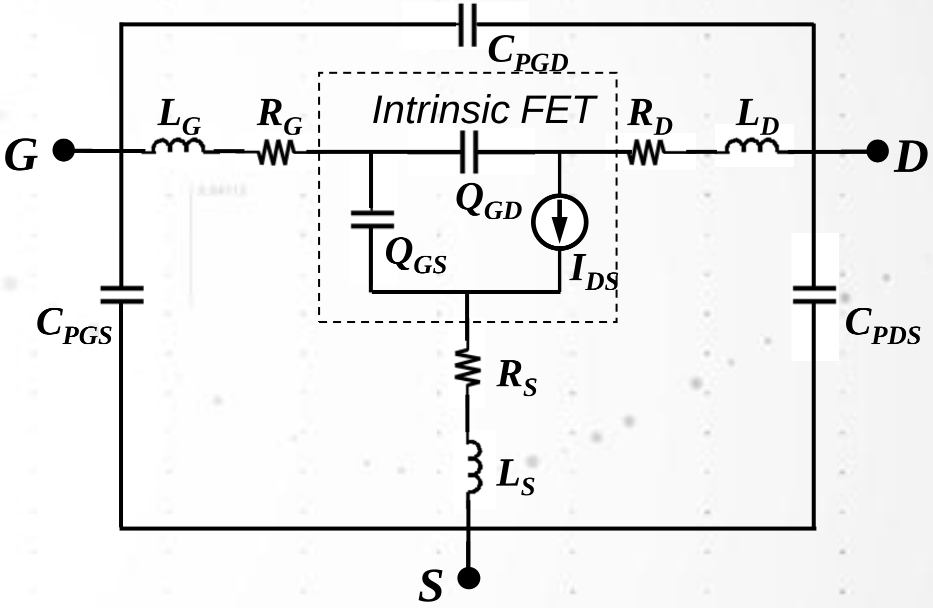
Vector Network Analyzer





Source Measurement Unit





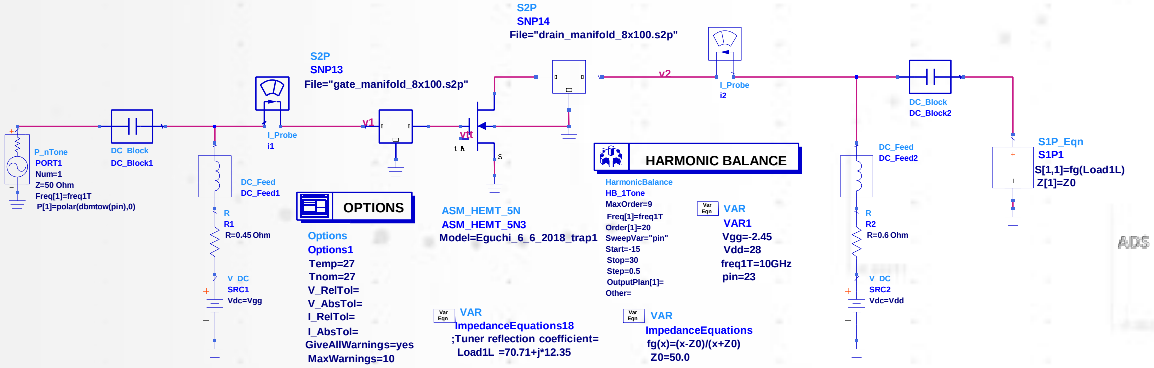
Source: Jianjun Xu and David Root, Keysight

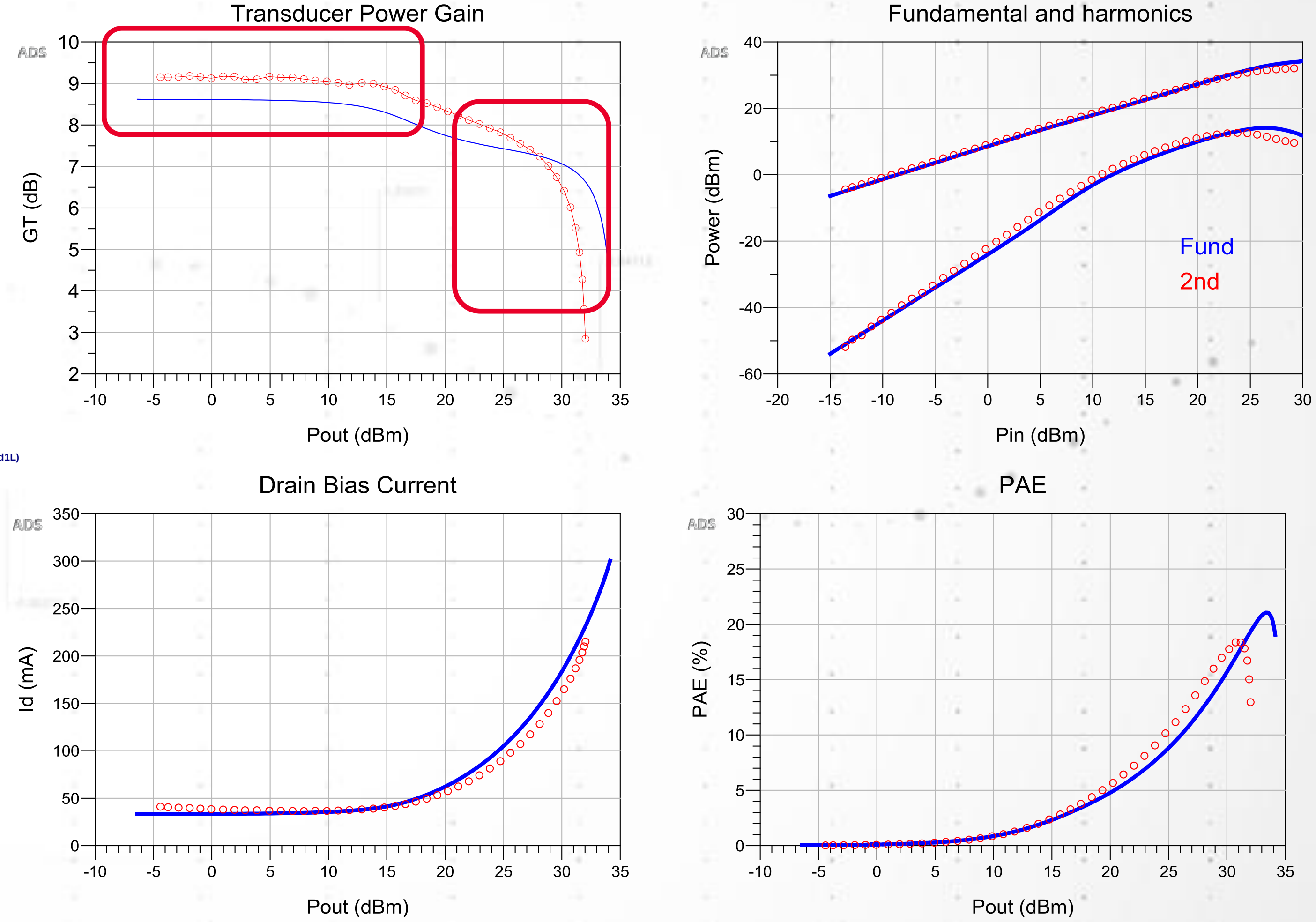

KEYSIGHT
MXG Analog Signal Generator
MXG
FREQUENCY
6.000 000 000 000 GHz
AMPLITUDE
-20.00 dBm
Amptd: -20.00 dBm
PNA-X
KEYSIGHT
PNA-X Network Analyzer
MAURY MICROWAVE
AUTOMATED TUNER
0.8 - 18.0 GHz
MT982BU
01
2345
SHIPPING SCREW POSITION: INITIALIZE AND SET CARRIAGE POSITION - 0
MAURY MICROWAVE
AUTOMATED TUNER
0.8 - 8 GHz
MT982EL
30
5004
MT964A2

Compact Model Optimization/Investigation

CASE STUDY: ASM-HEMT EXTRACTION

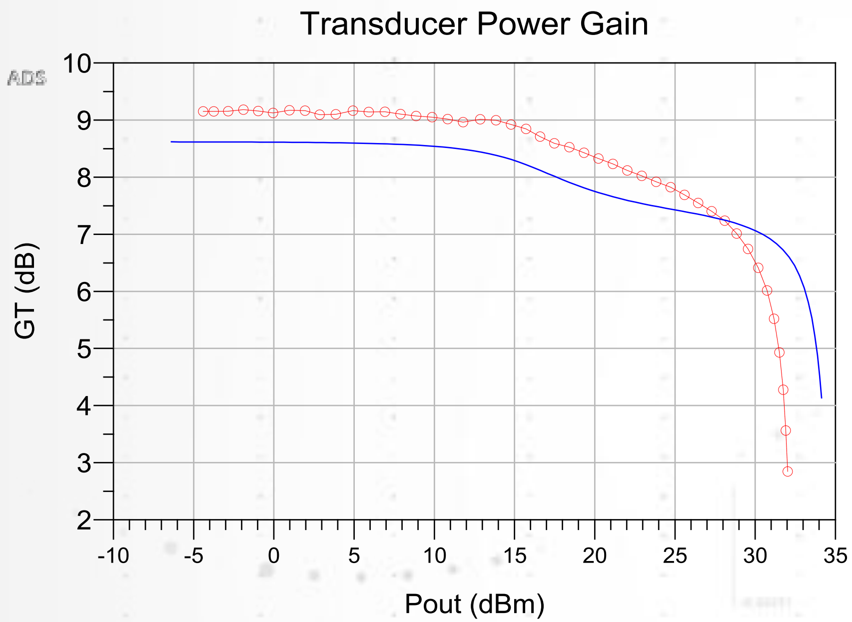
- Classic ASM-HEMT Extraction using DC-IV and S-parameter data





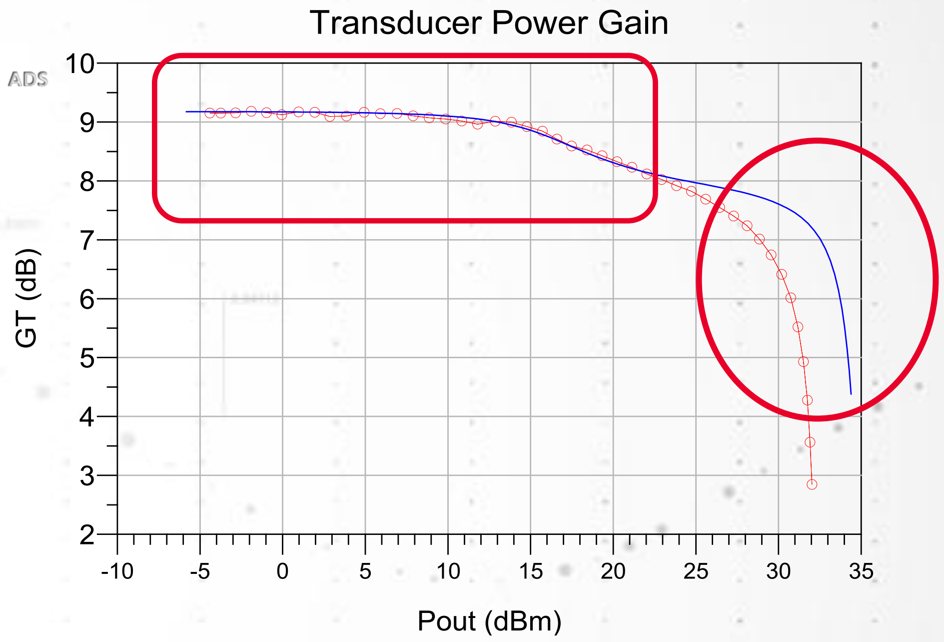
Device Data Courtesy of Qorvo, Inc.

Use Large Signal Data to Improve Model Parameters – Cgdo



Base model card

Cgdo:
from 100 fF to 90 fF

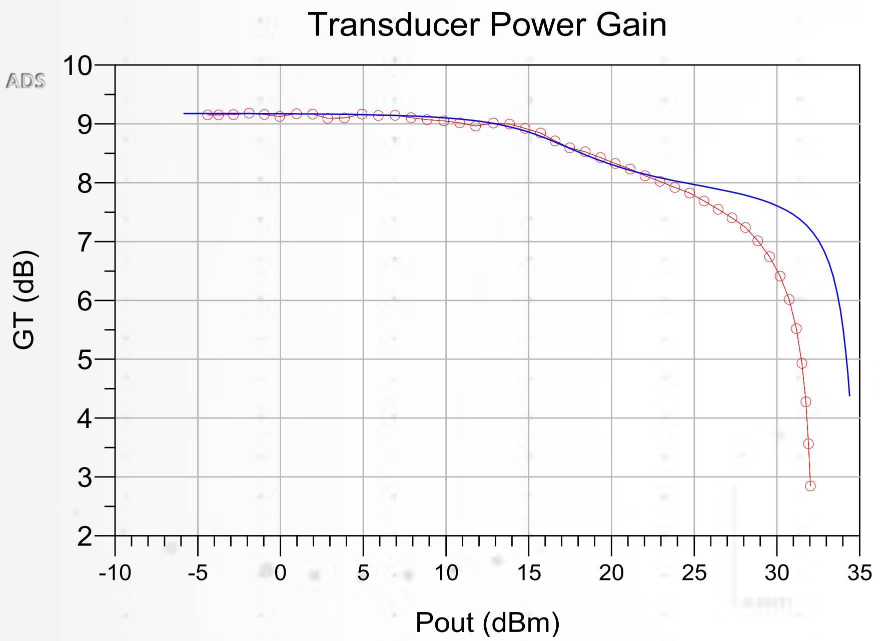


After
Cgdo = 90 fF

Transducer power gain (GT) is now well modeled at low Pout

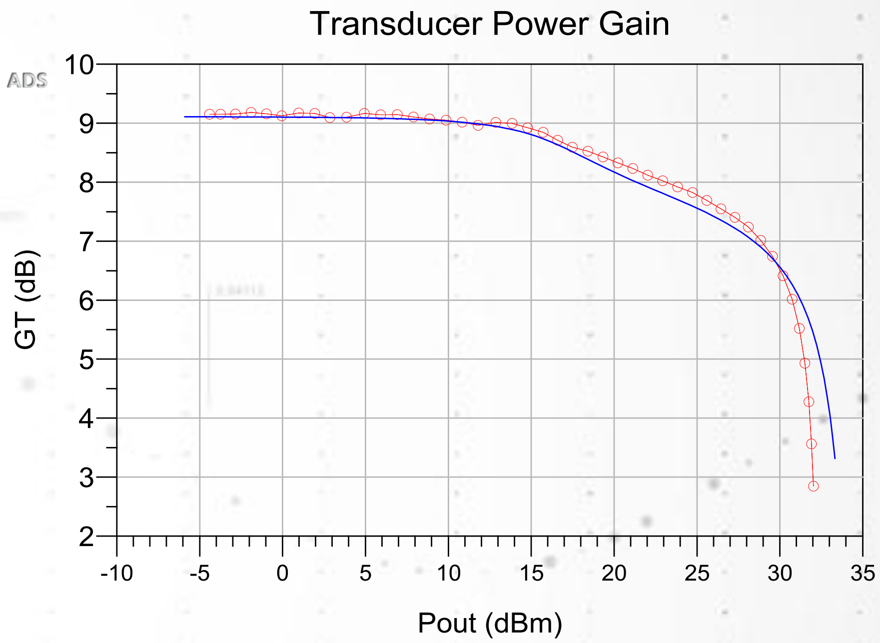
How about deep compression? (Pout > 25 dBm)

Model Parameter Improvement – Self-Heating



Before
- Cgdo = 90 fF

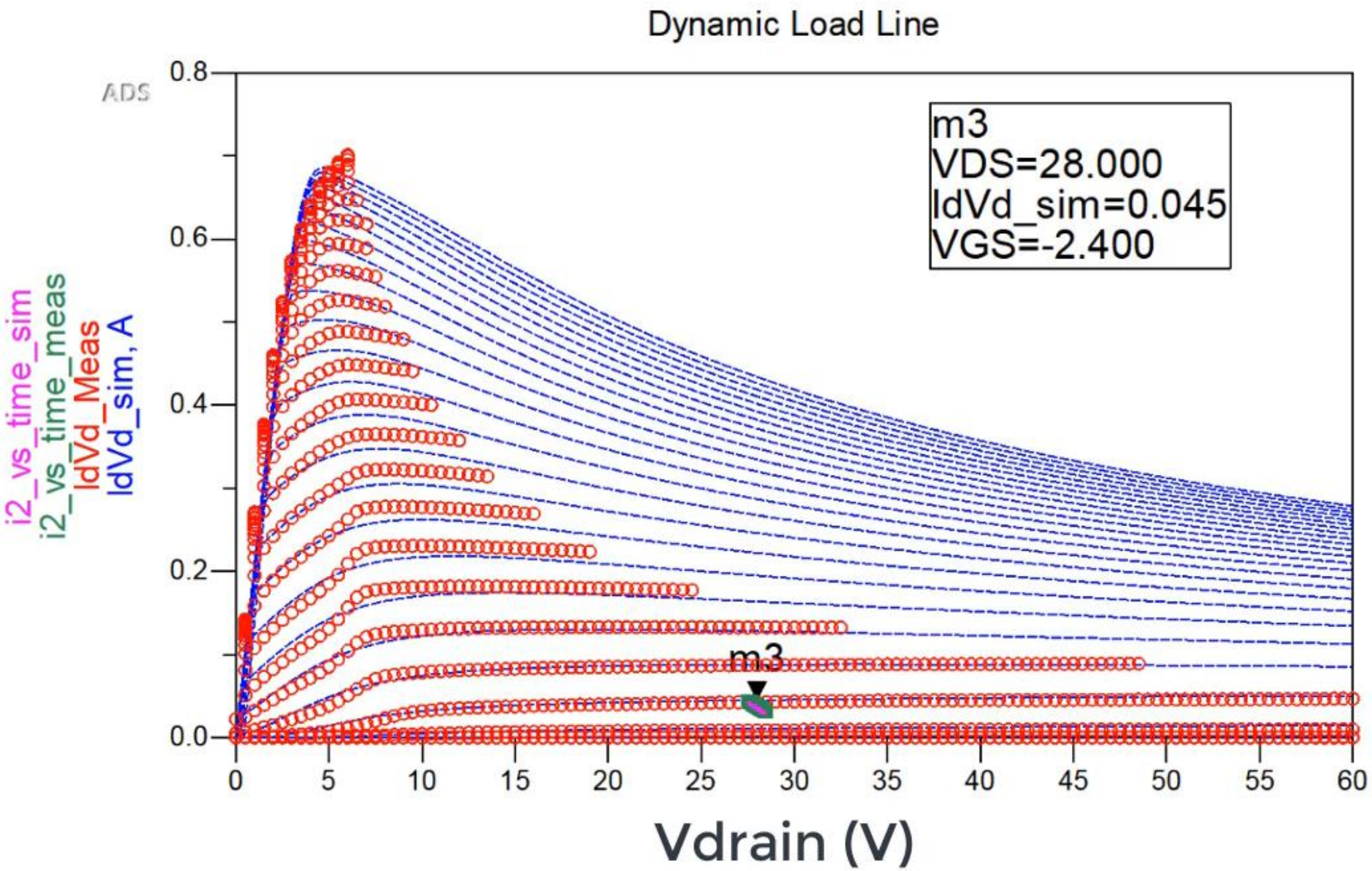
Tuning RTH and temperature coefficients

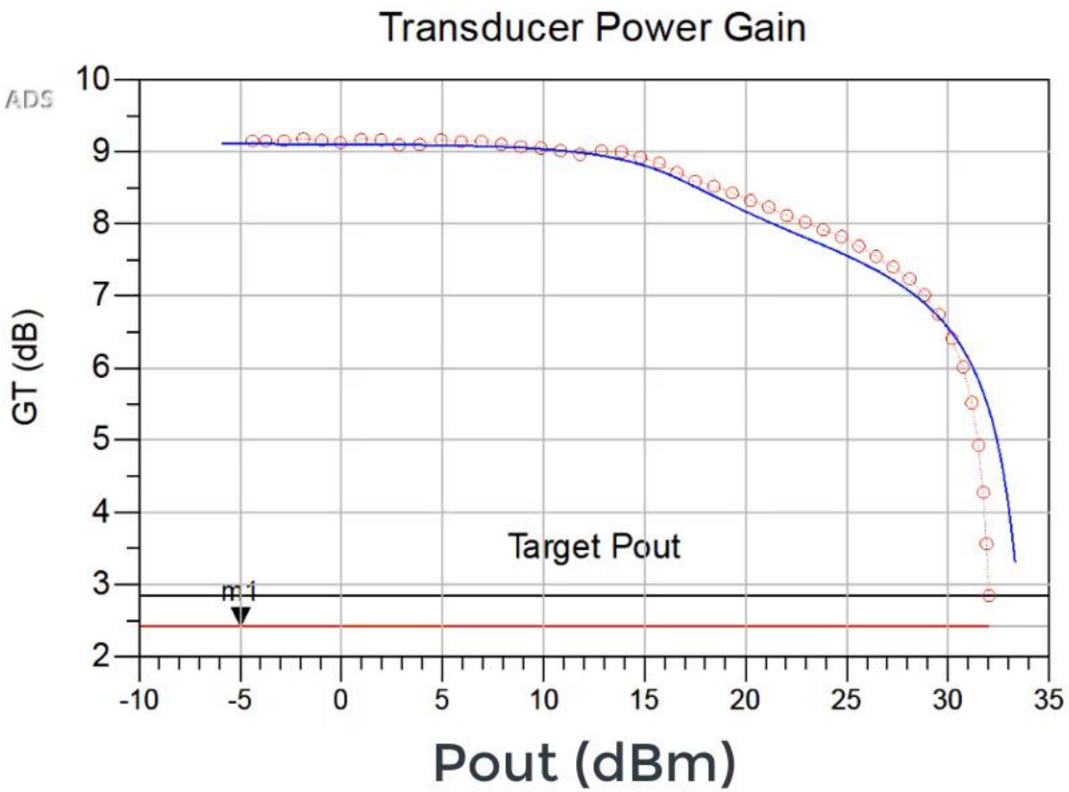


After
- Cgdo=90 fF
- Rth=20
- UTES=-2.97
- etc.

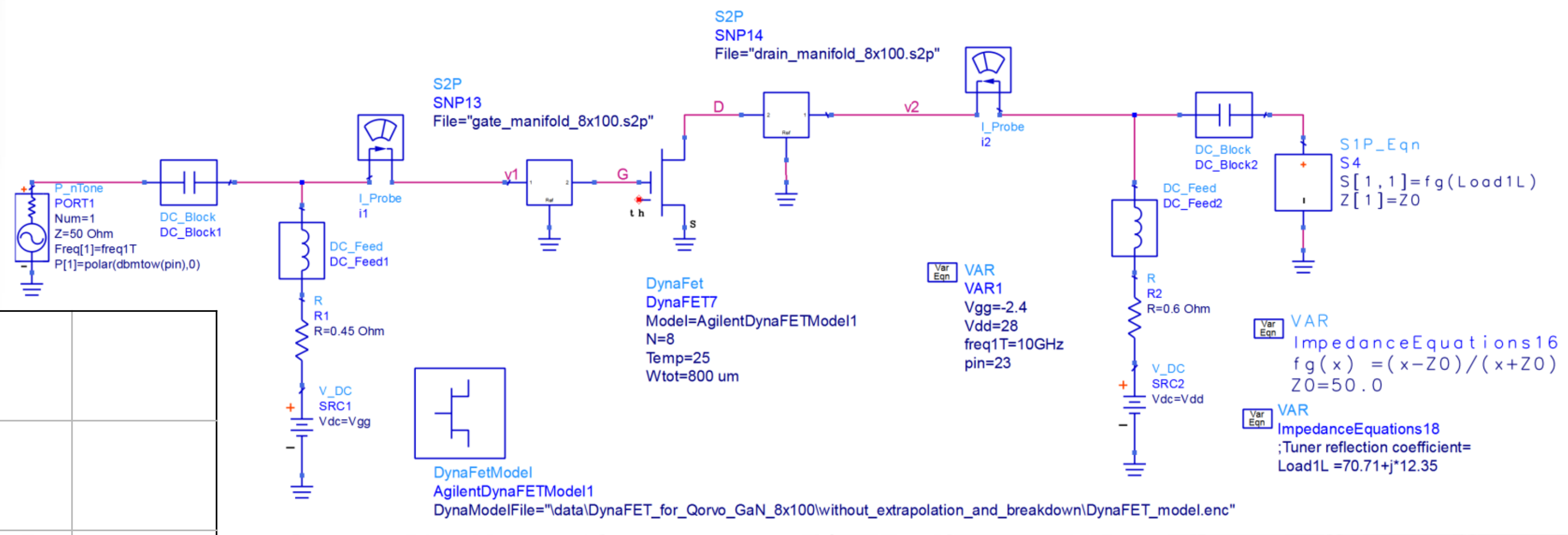
Transducer power gain (GT) is now well modeled over Pout

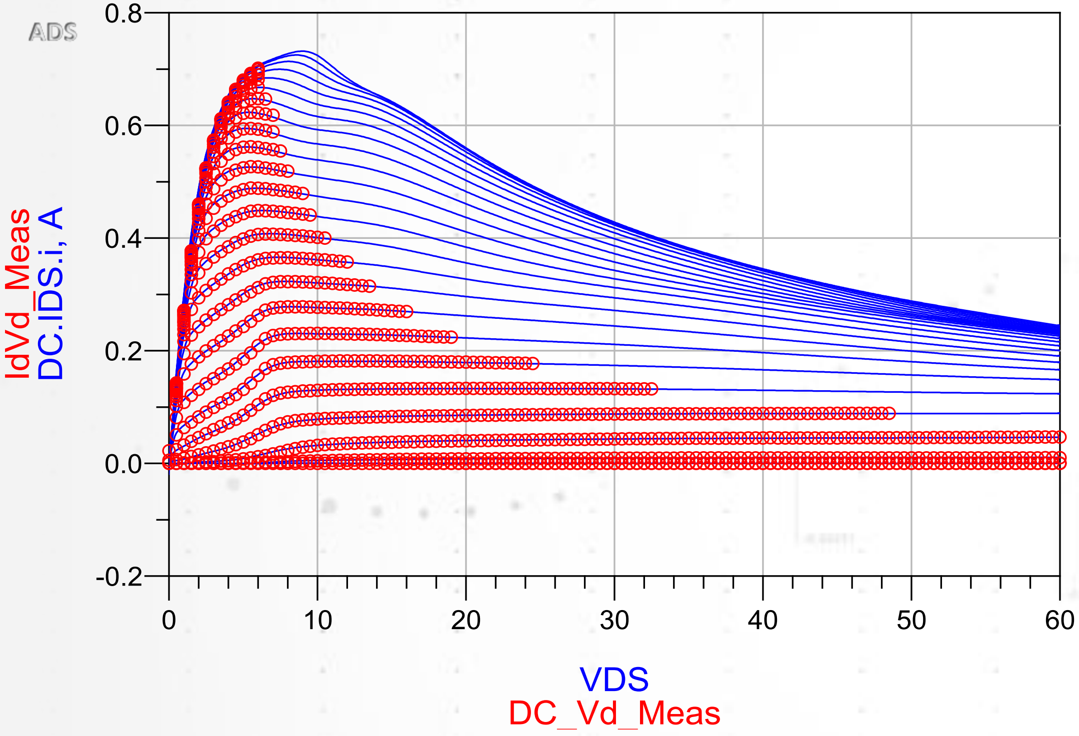
Dynamic Load Lines vs Pout

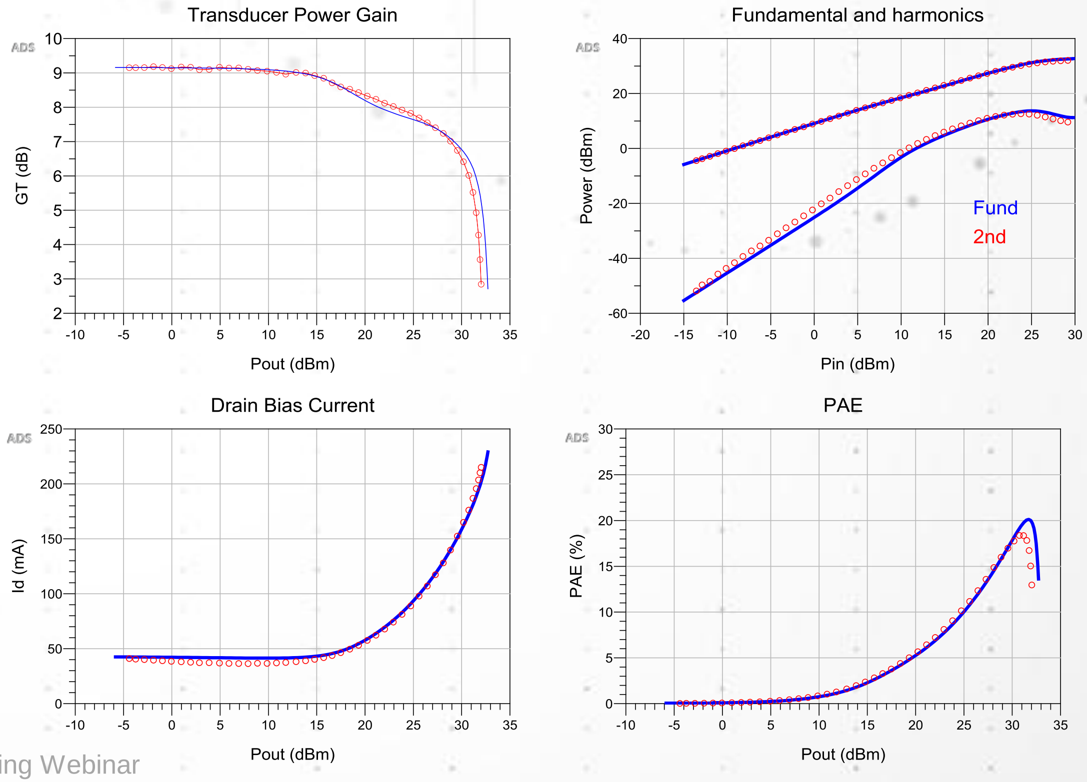




DynaFET Modeling







DynaFET model shows excellent agreement in all operation regions of the GaN HEMT. Universal applicable modeling approach.

To Recap…

- GaN technologies will grow.
- RF GaN modeling is challenging but extremely important.
- Easy to get this wrong – measurements, de-embedding, transformations, fitting, etc.
- Fortunately, we can help.

→Let's work together to enable better 1st pass design success!

keysight.com/find/eesof-iccap

keysight.com/find/eesof-innovations-in-eda

keysight.com/find/free_trials

Coming in spring 2019:
RF GaN extraction flows
- ASM-HEMT
- MVSG

For early access, contact:
Raj_Sodhi@Keysight.com